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SYNTHETIC TERRAIN IMAGERY FOR HELMET-MOUNTED DISPLAY, VOLUME 1

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In order to aggressively maneuver an aircraft at low altitude, the pilot must be aware of his attitude as well as the elevation of the surrounding terrain. Low altitude tactical maneuvering is difficult during day operations but becomes nearly impossible at night without an effective night attack system. A system that generates a terrain image from onboard data without the use of sensors would be valuable day or night under all weather conditions. Having a terrain image produced on a Helmet-Mounted Display (HMD) will provide a terrain reference wherever the pilot is looking, thus allowing for more aggressive tactical maneuvering at night. Therefore, with the advent of HMD technology, along with the ability to store a digital terrain data base on tactical aircraft, this capability can be realized. The overall objective of this program is to enhance tactical operations by utilizing a digital terrain system data base to generate a Synthetic Terrain Image (STI) on an HMD.

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1. Executive Summary

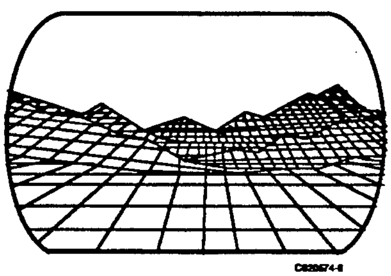
The purpose of this document is to provide a final report of the results of the Wright Labs sponsored (F33615-92-C-3601) program entitled "Synthetic Terrain Imagery for Helmet-Mounted Display."

Synthetic Terrain Images (STI) are created using elevation data from the U.S. Defense Mapping Agency's Digital Terrain Elevation Database (DTED). The DTED data used in this study was Level I, meaning the data points were separated by 100 meters. To display STI on a Helmet-Mounted Display (HMD), a view volume can be computed that comprises the instantaneous field of view (FOV) for the HMD, then a perspective rendering of the elevation data can be computed and displayed graphically on the HMD combiner lenses.

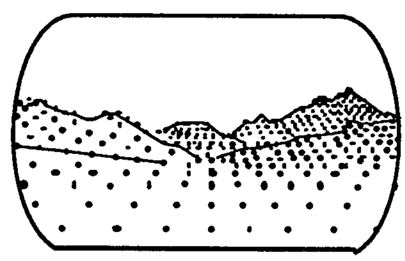
The Synthetic Terrain Image for Helmet-Mounted Display Study was a combined Honeywell/Lockheed Fort Worth Company effort. This study consisted of two phases. Specific tasks under Phase I included:

- Defining System Requirements.
- Developing Candidate Formats.
- Conducting a Part Task Evaluation for Format Downselect.

Two formats were preferred above the others. Both are geographically-fixed, meaning the rendered images appear to overlay the Earth's surface features.



Mesh



Points with Ridgelines

Phase II included:

- Enhancing selected Synthetic Terrain Imagery formats.
- Integrating those Formats into a Dome Simulator.
- Conducting a Full Mission Simulation.

A total of twelve USAF pilots, three Lockheed test pilots and one Lockheed engineer participated in the two simulations.

After assessing pilot performance data collected during the full mission simulation and comparing this data with subjective data collected through questionnaires as well as mission debriefings, the following conclusions/recommendations can be made:

Conclusions regarding Synthetic Terrain Imagery:

- Synthetic Terrain Imagery has limited utility when the pilot can see the ground.
- The system has great potential, optimum performance was obtained when coupled with Terrain Following Radar and a Forward Looking Infrared system (e.g., LANTIRN).

- Synthetic Terrain Imagery increases the time the pilot can fly in limited or zero visibility.
- Could allow for tactical maneuvering under Instrument Meterological Conditions.
- There is the potential to "close" the cockpit from the laser threat and to become more stealthy using Synthetic Terrain Imagery.

Recommended Improvements to Synthetic Terrain Imagery:

- Terrain should extend to the horizon.
- Synthetic imagery should look more like FLIR imagery.
- HMD symbology should look like HUD symbology.
- Any runtime performance improvements, in terms of increasing update rate, would be beneficial.

Overall, the concept of synthetic terrain appears to be a usable approach for providing the pilot off-axis terrain features. Current processor and graphics throughput are pushed to the absolute performance limit in terms of realtime update rate. Extending the STI image to the horizon, which increase the to-be-rendered view volume, places a greater demand on memory requirements, processor and graphics throughput, and is probably not achievable using current technology. However, the remarkable increases in processor speed and graphics throughput will likely enable this to be achieved in a very short time.

2. Introduction

2.1 Problem Statement. In order to aggressively maneuver an aircraft at low altitude, the pilot must be aware of his attitude as well as the elevation of the surrounding terrain. Low altitude tactical maneuvering is difficult during day operations but becomes nearly impossible at night without an effective night attack system. Only recently has technology evolved to the point where this is now becoming feasible. For example, Forward Looking Infra-Red (FLIR) sensors and Night Vision System (NVS) can provide terrain awareness at night under optimum weather conditions. Unfortunately, these systems do not work well under all environmental conditions and they do not provide adequate awareness over featureless terrain or open water. A system that generates a terrain image from onboard data without the use of sensors would be valuable day or night under all conditions. Having a terrain image produced on a Helmet-Mounted Display (HMD) will provide a terrain reference wherever the pilot is looking, thus allowing for low altitude tactical maneuvering, at night, beyond current FLIR system limits. Therefore, with the advent of HMD technology, along with the ability to store a digital terrain data base on tactical aircraft, this capability can be realized. The overall objective of this program was to enhance tactical operations by utilizing a digital terrain system data base to generate a Synthetic Terrain Image (STI) on an HMD.

2.2 The Solution. A system that generates a terrain image from onboard data without the use of sensors would be valuable day or night under all weather conditions. Having a terrain image produced on a Helmet-Mounted Display (HMD) will provide a terrain reference wherever the pilot is looking, thus allowing for more aggressive tactical maneuvering at night. Therefore, with the advent of HMD technology, along with the ability to store a digital terrain data base on tactical aircraft, this capability can be realized. The overall objective of this program is to enhance tactical operations by utilizing a digital terrain system data base to generate a Synthetic Terrain Image (STI) on an HMD.

2.3 Low Visibility Attack Mission Needs. The capability to employ day tactics on missions with low or degraded visual conditions has always been recognized as extremely beneficial, but only recently has the technology evolved to the point where this is now becoming feasible.

The operational requirements for a close air support/battlefield air interdiction (CAS/BAI) mission during periods of low or degraded visual conditions remain the same as for day ("severe clear") missions. For example, the aircraft must penetrate the threat environment and navigate to the target area. Once there, the pilot must acquire the target, properly maneuver the aircraft to deliver selected weapons, and safely egress.

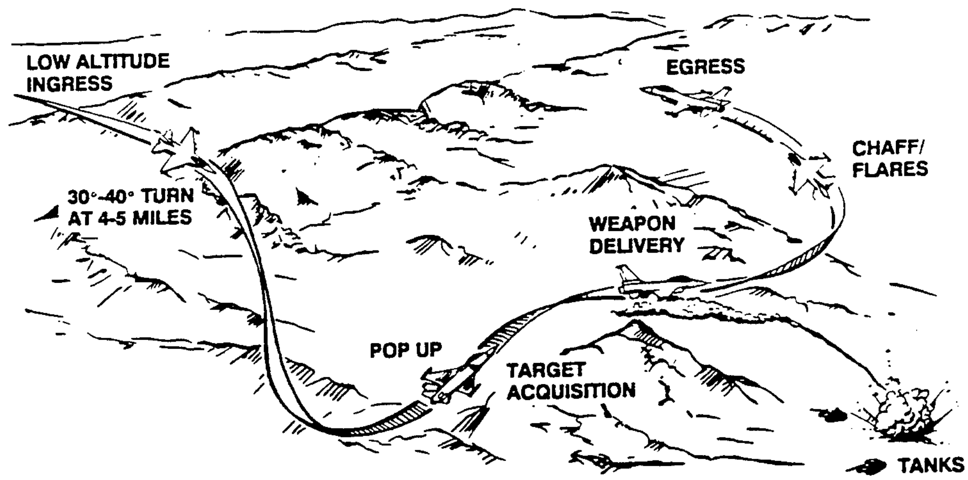


Figure 1
Weapon Delivery

An effective *vision enhancement* attack system would allow the pilot to ingress the target area at low altitude and acquire the target visually. The Low-Altitude Navigation and Targeting Infrared for Night system (LANTIRN) provides this capability using two equipment pods carried under the fuselage. One pod contains navigation equipment including, a terrain following radar and a forward-looking infrared (FLIR) sensor. The other pod contains targeting equipment including, a dual field-of-view FLIR tailored for target detection and lock-on, a target tracker, a boresight correlator for automatic missile hand-off, and a laser designator and rangefinder. Pilots report that the LANTIRN system is exceptional in its ability to present a clear image of the forward field-of-view in the wide field-of-view HUD under "good FLIR conditions" (low humidity and high thermal contrast).

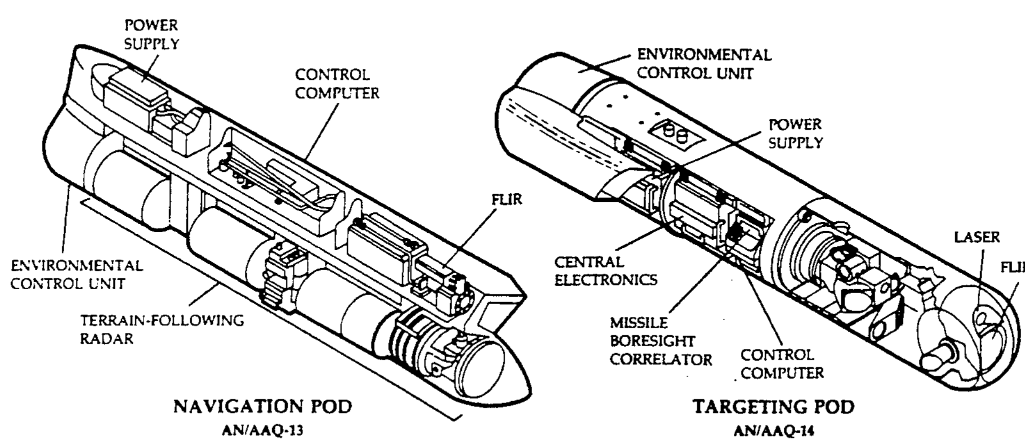


Figure 2
Low-Altitude Navigation and Targeting Infrared for Night system (LANTIRN)

Another technology solution for low visibility operations is to use Infrared Technology with a gimbaled sensor so that the field-of-view tracks that of the pilots direction of gaze. General Dynamics (now Lockheed-Ft. Worth) engaged in just such a endeavor with the Falcon Eye program. An infrared sensor was "caged" to follow the pilot's head movements so that the infrared image of where the pilot was looking was available. This provided the pilot with a means to acquire information in the visual scene around the aircraft much in the same way he would under normal day light conditions.

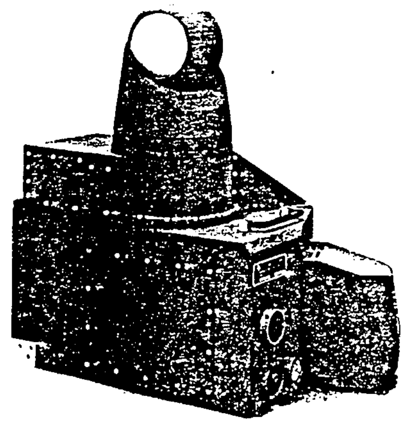


Figure 3
Falcon Eye Head-Steered Infrared (HSIR) Implementation

There are limitations to infrared technology. The most important is the conditions under which IR operates. If the relative humidity is high then IR presents a visual image with low contrast. Another condition which degrades IR performance is low thermal contrast. After the sun goes down there begins a cooling process that by morning has most objects cooled off to close to the ambient temperature. The thermal cooling process occurs every night, even in places with low relative humidity. In addition, the ability to see "all around the aircraft" is restricted with IR sensors. In the LANTIRN implementation there is a mechanization which allows pilots to slew the sensor in the direction of a turn to the left or right. Pilots report that viewing the terrain "going by sideways" in the HUD, which is intended to show a scene which is conformal to the outside visual scene, is disorienting. The HSIR on the other hand allows a pilot to look into left or right turns, yet does not meet all the operational requirements for head turning that exists on an attack mission. Azimuth requirements for utilizing a HSIR sensor will exceed 60 degrees during several segments of the attack profile. For example, during target ingress, the wingman could require azimuth angles exceeding 90-degrees to determine the leader's position. The wingman's azimuth to the target may exceed 60-degrees while maneuvering to retain the appropriate interval and spacing from the leader by delaying the pull-up in the target area. The leader may also require more than 90-degree azimuth coverage to acquire the wingman's position during the egress for mutual support and rejoin.

The role that STI can play is one of enhancing the capabilities of IR imagery. STI will always be available for extreme azimuth viewing requirements (i.e., greater than 60°), so it can augment even an HSIR equipped aircraft. Yet, a more near-term benefit for STI would be to complement LANTIRN equipped aircraft by providing off-axis terrain depiction to augment the pilots' terrain proximity awareness. STI can also be used when thermal contrast degrades to the point that the image quality of the IR is unusable, to that extent STI becomes a backup to IR technology to increase the probability of mission success.

3. Technical Approach

Goals for the terrain images include the following; (1) formats sufficient for terrain awareness during high speed low altitude flight, day or night, when the horizon is indistinct or obscured; and (2) awareness of height above the surface that cannot be judged visually under low visibility conditions. Display formats should provide terrain awareness over any surface. The formats should project minimal imagery necessary to provide the pilot with sufficient visual cues to determine approximate height above the surface, approximate distance to points on the surface, the motion of the aircraft relative to the surface, and, the relative proximity, shape, and size of terrain features. The terrain image needs to be detailed only enough to provide awareness of general terrain features. The pilot needs to perceive the terrain, but not have the image block or interfere with his view of the outside world or the cockpit. The image should be available in the full field of view of the HMD, and must be available not only in the direction of flight, but off-axis enough to permit aggressive, high-G maneuvering for terrain masking during the navigation phases of flight, as well as during offensive and defensive maneuvering.

STI can also provide the pilot with earth references to reduce the possibility of disorientation, particularly with respect to sky/ground orientation. In order to achieve the desired program goal, "synthetically" derived terrain depiction's will be rendered on the HMD to show the relative position of the earth (spatial relationship to aircraft and proximity) and gross features of the terrain.

It is useful to examine how STI formats can aid in the fulfillment of mission requirements. The following Table identifies the elements of the STI system that aid the pilot in accomplishing the mission requirements.

Table 1. STI aids to Mission Requirements

	Terrain Depiction	Horizon (Up/Down) Orientation	Motion Cues
Low Altitude Flight	X	X	X
Navigation			
Terrain Masking	X		X
Weapon Delivery	X		X
Pop-up Maneuver	X	X	X
Target Acquisition			

3.1 Helmet-Mounted Display Symbology. The HMD used for testing was the Honeywell I-NIGHTS HMD, see Figure 4. In addition to the STI, symbology is required to display primary flight reference information such as altitude, attitude, heading, speed, *etc*. Since STI testing was done in a "stock" F-16 cockpit, the existing head-up display (HUD) provided this information when the pilot looked forward toward the aircraft's system "boresight," see Figure 5. For off-axis viewing, an HMD symbol set, developed by General Dynamics for the F-16 *Night Attack Program Pilot-Vehicle Interface Study*, provided the information in the HMD, see Figure 6.

Figure 4
Honeywell I-NIGHTS HMD for F-16

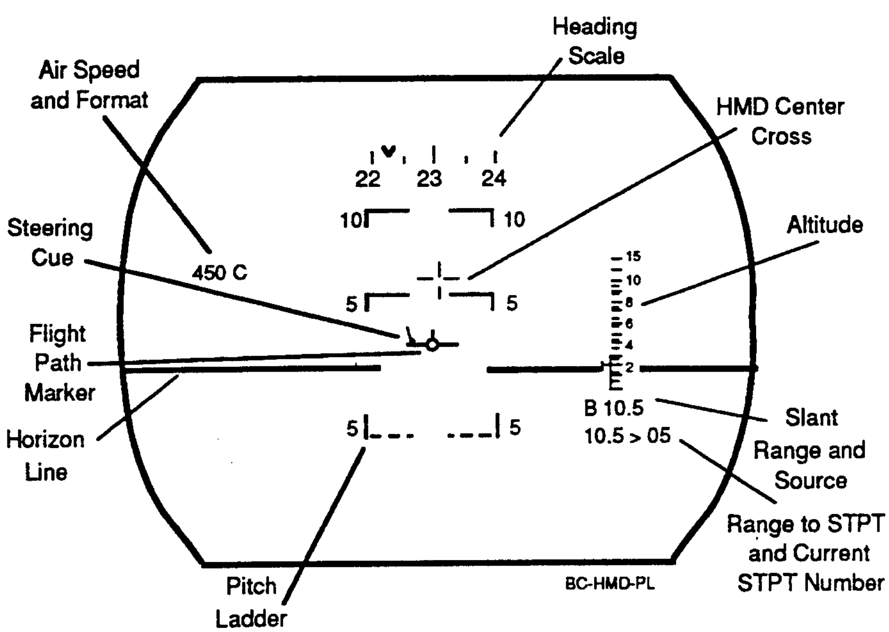


Figure 5
Boresight Symbology

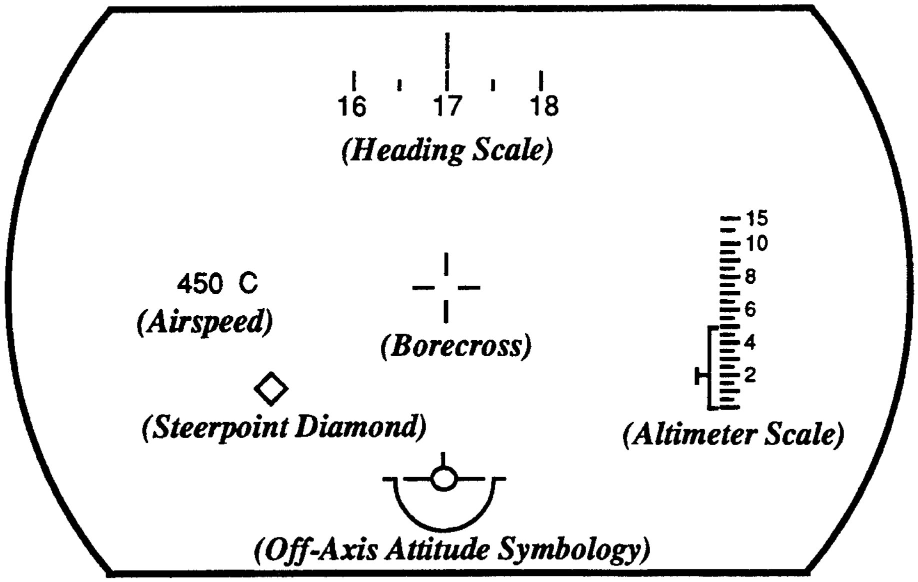


Figure 6
Off-Axis HMD Symbology

3.2 Rendering Approaches. In developing synthetic terrain formats two major areas were addressed. The first was to identify the characteristics of a terrain image that enhances spatial orientation. The second was to define the frame of reference for rendering the terrain image.

Format characteristics of an analog display that aid in the determination of spatial orientation are:

- Optical Flow - The acceleration of texture down the visual field.
- Linear Perspective - Parallel lines with a common vanishing point.
- Compression - The foreshortening of a projection as it is slanted away from the frontal plane.

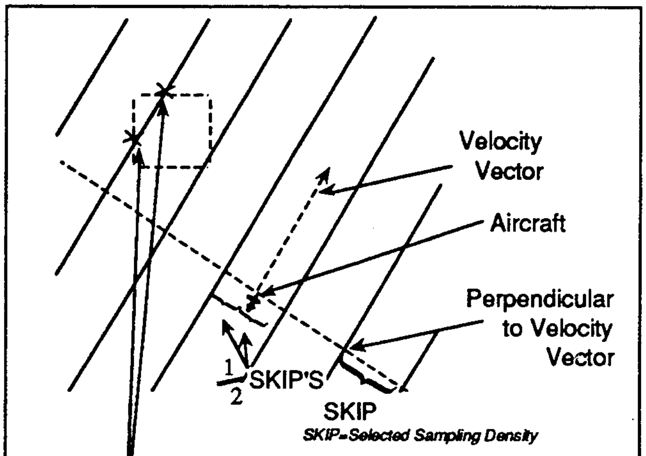
There are three possible frames of reference for viewing terrain imagery. These include:

- Aircraft centered
- Geographically Fixed
- Head Referenced

Six basic synthetic terrain formats have been developed that contain a combination of the above characteristics. These six formats will be evaluated in part task simulation. During part task simulation the pilots will also evaluate the concept of emergent detail. The following sections describe the six formats as well as the concept of emergent detail.

3.2.1 Aircraft Centered. This approach is an analog of linear perspective lines similar to those on an Attitude Director Indicator (ADI). All the rendered imagery has the aircraft as an anchor point.

3.2.1.1 Optical Expansion Gradient. The highest elevation points are represented as changes in the linear perspective lines of the gradient. This is the most computationally intensive of all the formats developed. Figure 7 illustrates the approach, which is based on projections parallel to the aircraft flight path vector. The process is cumbersome because the parallel projections must be surveyed to determine where they intersect lines connecting the x, y coordinates of the DTED database. At the point where the intersection occurs the elevation must be determined by computing the elevation between the two x, y coordinates, which then dictates the slope change of the projected line.



Where lines intersect "Grid," formed by connecting data base points, provide data regarding elevation changes which in turn dictate slope changes for rendered Expansion Gradient Lines

Figure 7
Rendering Routine for Expansion Gradient

The optical expansion gradient format is aircraft centered with the cockpit as the center of orientation, see Figure 8.

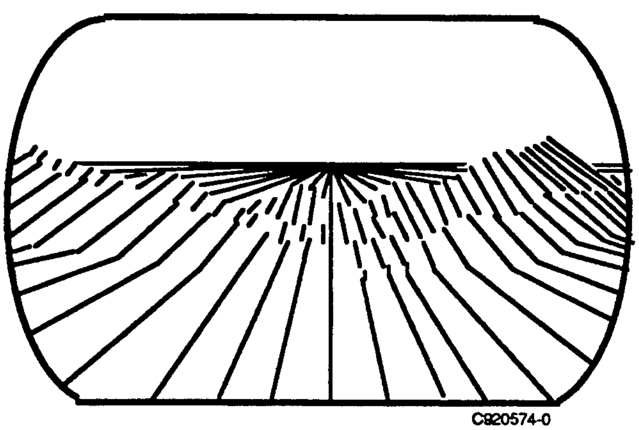


Figure 8
Expansion Gradient

3.2.1.2 Optical Expansion Gradient with Ridgelines. This is the expansion gradient format with a ray casting technique used to extract and draw ridge features. When a ray is projected and intersects a downturn in ground elevation it is stored in one of several arrays. The arrays contain data that "mask" other terrain points. The distance to the stored point is compared to the previous near field vertical point to determine which line it should be added to. After the projection is completed, any lines that have not had points added to them have a special 'flag' added to the point list, telling the system to end the line and allowing that array to be 're-used' later. Once a point has been stored in a line, the projection continues with no points being stored until the visual elevation exceeds the previous maximum, indicating that terrain is now visible behind the previous ridge, and any new downturn in visual angle represents a new ridge. Up to 8 ridges may be located along a single projection. Figure 9 illustrates the Ridgeline overlay on the Expansion Gradient.

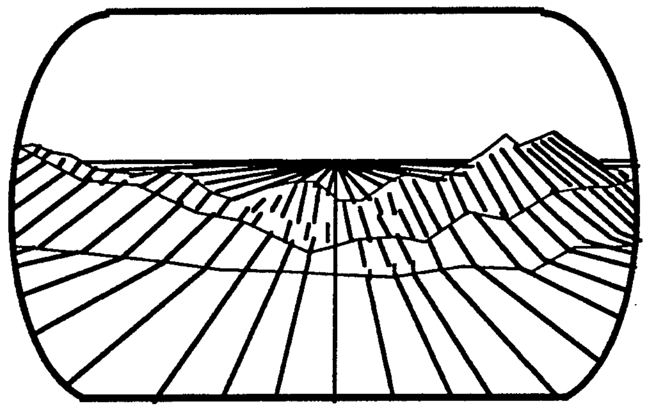


Figure 9
Gradient with Ridgelines

3.2.2 Geographically Fixed. This is the most intuitive format type. The formats are fixed to the earth's surface so maneuvering of the aircraft or the pilot turning his head has no effect on the format rendering process.

3.2.2.1 Points. This geographically centered format lights each sample point in the data base at the appropriate elevation. The rendering process is simplified by the Silicon Graphics' graphics library which has a machine language-level call (v3f) for drawing points in perspective with the x, y, z coordinates specified. Figure 10 illustrates the pointillist approach.

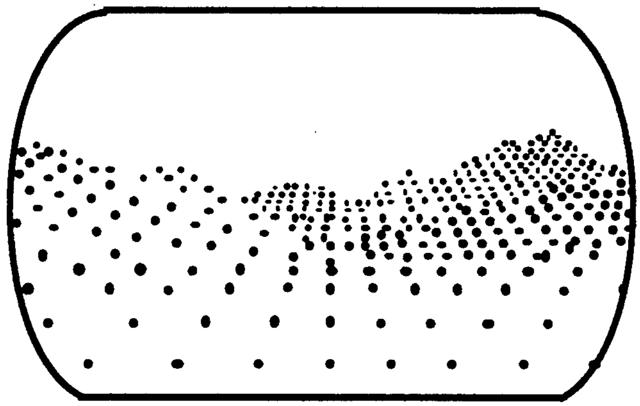


Figure 10
Points (Posttops)

3.2.2.2 Points with Ridgelines. Similar to the Optical Expansion format, ridgelines are drawn using the technique described previously. (see Figure 11).

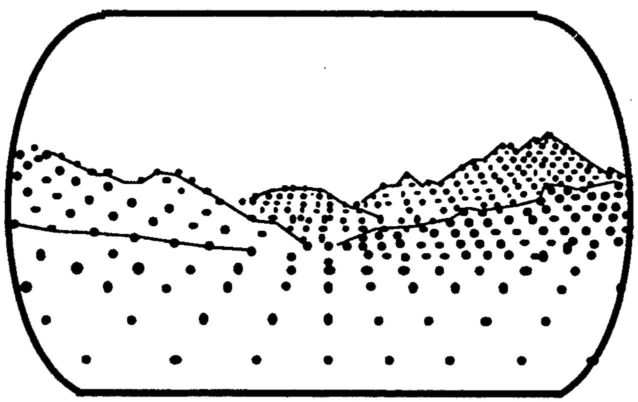


Figure 11
Points with Ridgelines

3.2.2.3 Mesh. This geographically fixed presentation scheme looks as though a large net were laid across the earth (Figure 12). The mesh or grid is deformed by topographic surface features. This rendering approach is similar to the Points format in that the v3f call from the Silicon Graphics' graphics library is used to draw the coordinates specified from the DTED database, then simple looping routines are used to draw lines connecting the points from East-to-West and then North-to-South.

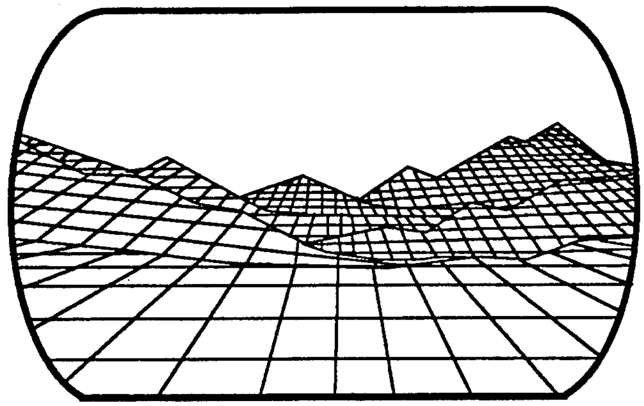


Figure 12
Mesh

3.2.2.4 Tiles. This format uses a straightforward routine to draw a tile at each point in the DTED database. There are two formulas in the tile drawing routine, to draw the lines along the x and y axis. The formulas ($X = P_x \pm 1/2$ reclen) and ($Y = P_y \pm 1/2$ reclen) draw the lines connecting the x and y coordinates, respectively. P_x and P_y are the x and y coordinates of the points from the DTED database, and reclen is user-specified length for the length of the tile side (this is accomplished with keyboard input, up & down arrows, while the software is running). The elevation, z coordinate, is determined by computing a bilinear interpolation between the adjacent x and y coordinates around the tile. Figure 13 illustrates the Tile rendering approach.

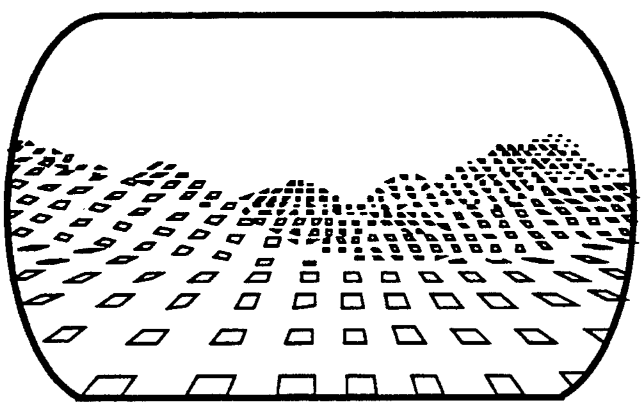


Figure 13
Tiles

3.2.2.5 Rectangular Tiles and Mesh. This is a hybrid format that combines the Mesh and offsets the Tile centerpoint using a constant that is $1/2$ the skip distance in the database (user selected value of 100, 200, 400 or 800m). The Tile formula is then simply modified in the following fashion: ($X = P_x \pm 1/2$ skip $\pm 1/2$ reclen) and ($Y = P_y \pm 1/2$ skip $\pm 1/2$ reclen). Figure 14 illustrates the hybrid combination of Mesh and Tiles.

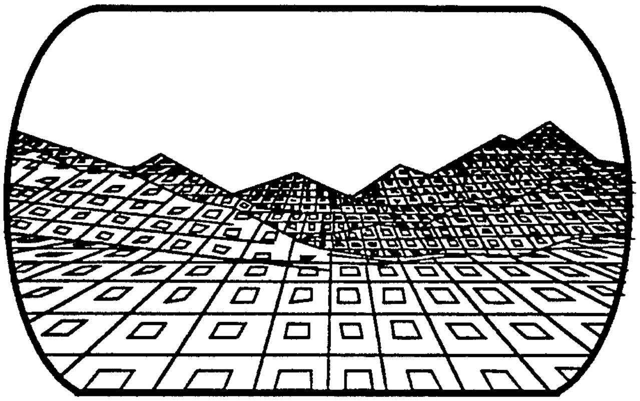


Figure 14
Rectangular Tiles and Mesh

3.2.3 Head Referenced. This rendering approach has all the rendering linked to pilot head position. This approach yields some interesting artifacts when maneuvering in one direction and turning the head in another.

3.2.3.1 Turning Orthogonal. The Ortho algorithm began with the requirement that the display of the terrain always be a grid orthographic to the line of sight (LOS) of the viewer, regardless of the orientation of the points of the terrain database. To improve speed in a multiprocessing environment, and to better emulate an aircraft, the task was divided into two parts. One section extracted data points (x,y,z) from the terrain database that, when connected as simple lines would form the display. The drawing display had to merely project the x,y,z coordinates of the points, in perspective, onto the HUD or HMD. This emulates a system on an aircraft where a computer, connected directly to the Digital Terrain System extracts the points from the database and hands them off to the display processor across the aircraft bus.

To determine LOS coordinates, a set of projections along the terrain is made starting 16° to the right of the LOS and ending 16° to the left of the LOS. For every projection, as it progresses, the distance along the LOS and perpendicular to the LOS is tracked. Each line is defined by a criterion distance, either along the LOS (h1-h4) or perpendicular to it (s1-s3 and r1-r3). As the projection crosses each criterion distance, the "current point" is added to the appropriate array. These then make up the points drawn. The current point is not necessarily the point over which the projection currently lies. As each point is extracted from the database, the change in z between the point and the aircraft height, divided by the distance along the projection, is computed. If the quotient is greater than the largest quotient so far then the point represents the greatest visual elevation seen so far, and becomes the current point. If it is less than the maximum visual elevation, the previous current point is masked by the terrain by a higher elevation during the current projection sample. The h line criteria begin at 1.5, 3.0, and 4.5, and 6.0 NM along the LOS. To provide the illusion of movement over the terrain, the distance flown since the last update is subtracted from the criteria each frame. When the h1 criteria reaches 0 NM, each line is shifted up and a new criteria is established at h3 criteria + 1.5 NM.

To draw the lines each of the 10 lines (s1-s3, r1-r3, and h1-h4) out in front of the LOS is stored as a simple array of x,y,z's forming the lines. Since the rendering is based upon LOS there is no hidden surface removal required. The s1 and r1 criteria are a fixed distance away from the LOS. Each subsequent line is a fixed distance from the previous line, so when viewed while the aircraft is in motion, the aircraft appears to be halfway between s1 and r1. The "turning" effect is generated by applying a bias, based on turn rate, to the s and r criteria so that the lines are shifted across the field of view as the aircraft turns. Note that, as a result, the turning of the grid will be at a frame rate of the extraction process rather than the drawing process (see Figure 15).

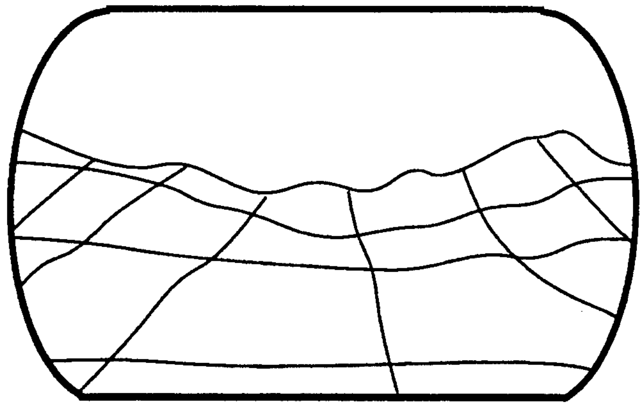
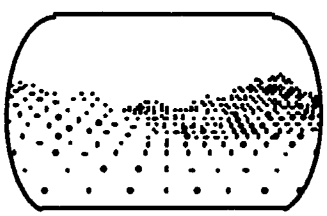


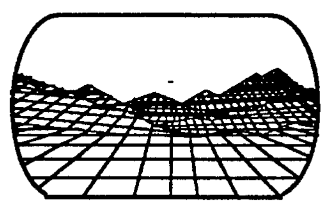
Figure 15
Turning Orthogonal

There are two main drawbacks to the Turning Orthogonal format. The first is that entire terrain features that exist between the lines disappear due to line spacing. The other drawback is that the lines are "orthogonal" to the line of sight of the pilot, so even if the pilot looks to the side or rearward it appears that the lines are moving toward the pilot.

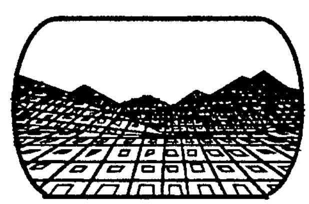
3.2.4 Emergent Detail. The concept of emerging detail assumes that more terrain detail is needed at lower altitudes. Therefore, more terrain detail is provided as the aircraft passes through various set clearance planes. For example, flying above 2000 feet AGL, a less detailed STI format may be displayed. When descending below 2000 feet, another more detailed format would then be displayed. Descending below 500 feet, a very detailed terrain picture would be shown. Figure 16 depicts one possible combination.



Above 2,000 ft. AGL



Below 2,000 ft. AGL



Below 500 ft. AGL

Figure 16
Emergent Detail Approach

3.3 Other STI Factors. Pilot acceptance of the various STI formats may be affected by sampling density and view volume. Sampling density is the distance between points from which lines are drawn. The greatest sampling density available samples the terrain data every 100 meters. Sample spacing can be set at 100, 200, 400, or 800 meters. Sampling density has a direct effect on speed of graphics processing. The more dense the sampling density (i.e., the smaller the number) the slower the graphics processing. The view volume is the distance from the closest terrain depiction out to the STI horizon. View volume can be selected from 1 to 6 NM where the greater the view volume, the slower the graphics processing. For tactical aircraft traveling at speeds of 8 miles/minute (480 kts) a minimum required view volume is 5-6 NM. A 5 or 6 NM view volume provides the pilot approximately 37.5 to 45 seconds of "look ahead" time. In order to maximize the pilot's ability to see into the distance a 6 NM view volume was adopted for the Part-Task evaluation.

3.4 Hidden Surface Removal. Several of the formats need to have hidden points/lines removed. This is accomplished by drawing the terrain as a black surface just below the actual elevation data to allow the zbuffer to correctly determine if the point or line should be drawn or not.

Simulation Testing

This program was a two phase effort. Phase I, which was completed in January 1993, formulated concepts and demonstrated STI presentation approaches in a Cockpit Development Station (CDS). Specific tasks accomplished were:

- Define System Requirements
- Develop Candidate STI Formats
- Integrate Formats into a Cockpit Development Station
- Conduct Part Task Evaluations

Phase II, which was completed in September 1993, further developed the most promising STI formats and evaluated those formats in a dome simulator. Specific tasks included:

- Enhancing STI Formats
- Integrating Selected Formats into a Dome Simulator
- Conducting a Full Mission Simulation

4. Part-Task Evaluation

In order to determine the feasibility of STI, as well as determine pilot format preference, a preliminary investigation in a Part-Task simulation was conducted.

4.1 Part Task Evaluation Objectives. The overall objective of the part task simulation was to evaluate various STI formats with respect to pilot acceptability. For example, the image quality of the formats should allow sufficient terrain awareness for high speed, low altitude flight when the horizon is indistinct or obscured. Display formats should provide terrain awareness over any surface with adequate detail to show relative proximity, shape, and size of terrain features. Additionally, the pilot should be provided sufficient visual cues to determine approximate height above the ground and relative aircraft motion with respect to the surface. The terrain image should not block or interfere with the pilots' view of the outside world or Head-Up Display (HUD) symbology. The image should be available in the full field-of-view of an HMD to enable off-axis viewing of the surrounding terrain and permit aggressive maneuvering for terrain masking. This design effort will involve assessing pilot visual perception and other human factors considerations.

4.2 Facility Description. The part task portion of the STI study was conducted in the Cockpit Development Station located adjacent to the Flight Simulation Laboratory (FSL). This facility contains an F-16 Block 50 cockpit mockup. The cockpit displays that are operable include two Multi Function Displays (MFDs), a Radar Warning Receiver (RWR) and a Data Entry Display (DED). Six feet in front of the cockpit is a projection screen on which a fixed FLIR image of the outside visual scene was shown superimposed with HUD symbology. Additionally, the sidestick, throttle, and up-front controls are functional. All other cockpit displays and controls are static representations. This arrangement is shown in Figure 17.

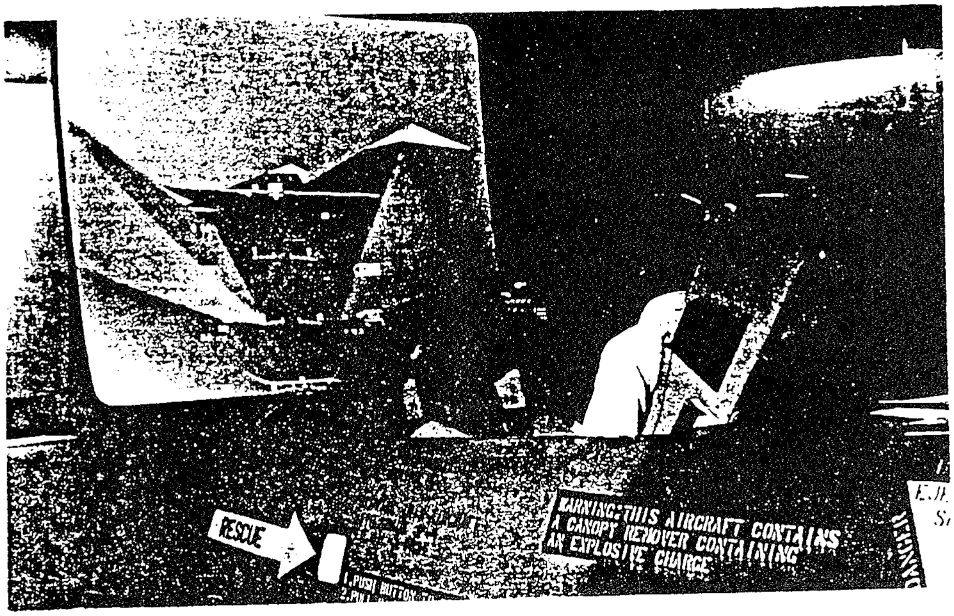


Figure 17
Pilot-Vehicle Integration Development Station

4.3 Subjective Evaluation Procedure. This segment of the evaluation enabled each pilot to become familiar with the six candidate STI formats while providing adequate training to perform the more operationally oriented Route Navigation and Terrain Masking segments. Both these tasks can be achieved simultaneously with Low Altitude Step-Down Training (LASDT) using the HMD. Low level navigation, terrain masking, hard turns and break turns were flown in the 300 ft. to 500 ft. low altitude block.

The primary objective of this portion of the evaluation was to determine the pilots' preferred STI formats and the relative ranking of the formats on the basis of providing terrain awareness cues. The subjective format evaluation was conducted in four phases:

4.3.1 Phase 1. Pilots viewed all formats once to learn the terminology/descriptors for each format and to familiarize themselves with using an HMD. Pilots evaluated each STI format with different sampling densities in an alternating increasing/decreasing presentation sequence to determine the desired setting. View volume (how far in the distance the display renders the terrain) was set to the largest view volume (6 NM).

It was expected that pilots would have a negative reaction to the slower update rates caused by higher sampling densities (shorter sampling intervals). The update rate for each sampling density and the pilots-preferred sampling density would also be used to investigate the "cross over" point where the sampling density incurs an update rate penalty.

4.3.2 Phase 2. Each pilot viewed the Mesh STI format as the update rate was varied between 10, 15, 20, 25 and 30 hertz in an alternating increasing/decreasing order. Pilots performed a series of 90° hard turns, where the effect of a delayed update is most pronounced, to determine if the update rate was acceptable.

4.3.3 Phase 3. Each pilot performed the LASDT procedure with each STI format and ranked the formats in order of most preferred to least preferred, relative to the degree that each format was perceived to provide terrain awareness cues. An initial four level categorization was applied consisting of +, 0, -, and -- (best to worst) to apply a screening of the options. Through iterations, these top level categories were converted to a numerical ranking. Iterations were made at the discretion of the pilot until he felt able to rank the six options from best/most informative to worst/least informative along the dimension of terrain awareness. Subjective comments were taken at the completion of this phase.

4.3.4 Phase 4. An emergent detail STI format combination was demonstrated and a questionnaire was used to elicit concepts and ideas for an improved emergent detail presentation and format combination.

4.4 Route Navigation. The objective of this evaluation is to determine pilot performance benefits provided by synthetic terrain or a particular synthetic terrain format in both flat/rolling and rugged terrain conditions.

Each pilot flew a low level navigation route with an IP to target run. The flight proceeded through flat/rolling or rough terrain for approximately 6-8 minutes. Two comparable flat/rolling terrain routes and two equivalent "rough" terrain routes were used for this portion of the evaluation. The pilots were asked to maintain a 300 ft. to 500 ft. AGL altitude block and 480 knots enroute to the IP and 540 knots enroute to the target.

It was hypothesized that the synthetic terrain images would allow the pilot to 1) maintain a lower average altitude and 2) vary in altitude less over the course of the mission. It was also hypothesized that the pilot would maintain a higher average airspeed and have less variation in speed with the benefit of synthetic terrain. Synthetic terrain was also expected to reduce deviation in pitch, sharp changes in pitch, and ground collision. It is believed that these performance measures reflect the pilot's comfort level. Increasing a pilot's look time off-axis was also expected to reflect increasing comfort level. When the pilot feels more comfortable and more in control of the situation he will look off-axis longer and more frequently. The benefit of synthetic terrain was expected to be influenced by terrain conditions with STI showing a more pronounced benefit under rugged terrain conditions.

In this segment of the evaluation four STI formats were compared to a baseline condition of no STI (HUD data only) under two terrain conditions. Therefore, each pilot made a total of ten runs to evaluate every combination of STI formats and terrain conditions. The order in which the pilot made the ten runs was randomized over all pilots to balance any learning effects across all STI format and terrain combinations. No asymmetrical transfer of learning effects was expected between format presentations since the familiarization and training procedures built into the evaluation process were expected to eliminate these effects. The two flat/rolling terrain routes as well as the two rough terrain routes were alternated. This reduced any carry over information learned about the route's terrain features from one run to the next.

The counter-balanced design is presented in Table 2.

Table 2. A randomized experimental design matrix for the Route Navigation runs

	Experiment Trials									
Pilot	1	2	3	4	5	6	7	8	9	10
1	Points Rugged	No STI Rugged	Mesh Flat	No STI Flat	Grad Flat	Mesh Rugged	Ortho Rugged	Grad Rugged	Points Flat	Ortho Flat
2	Grad Rugged	Mesh Flat	Grad Flat	Points Rugged	Ortho Rugged	No STI Rugged	Ortho Flat	Mesh Rugged	No STI Flat	Points Flat
3	Ortho Flat	No STI Rugged	Ortho Rugged	Points Flat	No STI Flat	Mesh Flat	Grad Rugged	Points Rugged	Grad Flat	Mesh Rugged
4	Points Rugged	No STI Rugged	Grad Flat	No STI Flat	Grad Rugged	Points Flat	Mesh Flat	Ortho Flat	Mesh Rugged	Ortho Rugged
5	Mesh Rugged	Ortho Rugged	Mesh Flat	Points Rugged	No STI Rugged	Grad Rugged	No STI Flat	Points Flat	Ortho Flat	Grad Flat
6	No STI Rugged	Grad Rugged	No STI Flat	Ortho Flat	Mesh Flat	Grad Flat	Points Flat	Mesh Rugged	Ortho Rugged	Points Rugged
7	No STI Flat	Mesh Rugged	Grad Flat	Ortho Flat	Points Rugged	Ortho Rugged	No STI Rugged	Grad Rugged	Mesh Flat	Points Flat
8	Grad Rugged	Mesh Rugged	No STI Rugged	Ortho Rugged	Mesh Flat	Points Flat	Grad Flat	No STI Flat	Points Rugged	Ortho Flat
9	Ortho Rugged	Points Flat	Grad Flat	Mesh Rugged	No STI Rugged	Ortho Flat	No STI Flat	Mesh Flat	Grad Rugged	Points Rugged
10	Points Flat	No STI Flat	Points Rugged	Grad Rugged	Mesh Flat	No STI Rugged	Mesh Rugged	Ortho Rugged	Grad Flat	Ortho Flat

Table RN

The following data was collected during the course of each mission: aircraft altitude, speed, pitch, pilot's head azimuth, and elevation. From this data a number of metrics was computed to measure pilot performance. Average altitude indicates the pilot's ability to stay as low as possible for selected mission segments. The altitude deviation was computed as the integrated deviation in altitude. This measure is termed the Root Mean Square Error (RMSE), where larger values indicate greater deviations in altitude along the flight path. Average speed reflects how fast the pilot feels comfortable flying the aircraft at low altitude. The speed deviation was computed as the integrated deviation by the RMSE method and is an indication of the pilot's ability to maintain constant speed. Pitch deviation was also computed as the integrated deviation using the RMSE method. Total look time off-axis and average look time off-axis was recorded. A count of sharp pitch changes, greater than $\pm 40^{o}$, and ground collisions was also tallied on the Route Navigation task.

Tests for statistical significance were computed using a 5 X 2 X 2 (format by terrain by direction) repeated measures analysis of variance (ANOVA) statistic for the average altitude, RMSE altitude, average speed, RMSE speed and RMSE pitch metrics with pilot, STI format and terrain conditions as factors in the analysis. The frequency of sharp pitch changes and the frequency of ground collisions will be computed. A Chi Square statistic was then be used to test statistical significance with pilot, STI format and terrain conditions as factors.

4.4.1 Performance Variables. The following provides a description of the mathematical formulas used to generate the performance data.

All averages and standard deviations are straight forward:

Let X_i = a single observation (altitude, velocity, or pitch)
N = the number of observations

Average is the sum of observations divided by the number of observations.

FORMULA: Average $X = (\sum X_i) / N$

Standard Deviation = square root of [{sum of (observations squared) minus number of observations times (sum of observations) squared} divided by {number of observations minus 1)]

FORMULA: Standard Deviation $X = \sqrt{ [\{X_i^2) - N * (\sum X_i)^2 \} / \{N-1\}] }$

Root Mean Square was calculated as follows:

Root Mean Square is the square root of [sum of (pitch squared)].

FORMULA: Root Mean Square PITCH = $\sqrt{[\sum (PITCH_i)^2]}$

Another method was used for calculating RMS. for deviations from assigned "block" values.

Root Mean Square is the square root of [sum of (deviations from block altitude squared)].

FORMULA: Root Mean Square ALTITUDE = $\sqrt{[\sum (DEV\_ALT_i)^2]}$,

where,

$$DEV\_ALT_i = \begin{cases} \text{altitude} - 500, & \text{if altitude} > 500 \text{ ft.} \\ 0, & \text{if } 300 \text{ ft.} \leq \text{altitude} \leq 500 \text{ ft.} \\ 300 - \text{altitude}, & \text{if altitude} < 300 \text{ ft.} \end{cases}$$

Similarly,

Root Mean Square VELOCITY = $\sqrt{[\sum (DEV\_VEL_i)^2]}$,

where,

$$DEV\_VELi = \begin{cases} 480 - \text{velocity}, & \text{if velocity} < 480 \text{ knots} \\ 0, & \text{if } 480 \leq \text{velocity} \leq 700 \\ \text{velocity} - 700, & \text{if velocity} > 700 \text{ knots} \end{cases}$$

Number of Ground Strikes:

Ground strikes was a counter of the number of times aircraft altitude changed from positive to negative as measured in height above ground level (AGL).

Gaze Time Off-Axis:

Off-axis was defined as helmet elevation greater than 10° from horizontal or helmet azimuth greater than 15° from straight ahead.

For Time Off-Axis a variable was set to 1 if the pilot's head was turned off-axis and 0 otherwise at each data point collected. Therefore, the time off-axis was the length of time that the off-axis variable was continuously 1 and each continuous string of 1's was a single look off-axis.

Let T_i = length of time for a single continuous look off-axis
n = number of such time intervals

Then, the average and standard deviation of time off-axis were computed using the same formula as described previously.

FORMULA: Average Time Off-Axis = $(\Sigma T_i) / n$
Standard Deviation X = $\sqrt{[\{T_i^2) - N * (\Sigma T_i)^2\} / \{N-1\}]}$

Percentage of Gaze Time Off-Axis:

The percent of time off-axis is computed as the sum of the off-axis variable 1's and 0's divided by the number of observations.

FORMULA: Percentage of Time Off-Axis = $(\Sigma \text{Off-Axis}_i) / n$

Significant (Dangerous) Pitch Situations:

A significant pitch situation is defined as pitch angles below -10°.

That is,

$$SIG\_PITCH = \{ \begin{array}{ll} 1, & \text{if aircraft pitch} < -10°; \\ 0, & \text{otherwise}\} \end{array}$$

Therefore, the time with significant pitch was the length of time that the SIG_PITCH variable was continuously 1 and each continuous string of 1's was a single significant pitch situation.

so, T_i = time duration of the significant pitch situation
n = number of such time intervals.

Then, the average and standard deviation of significant pitch intervals was the usual average and standard deviation.

4.5 Terrain Masking. The evaluation objective of this segment was to measure the pilot's Terrain Masking improvement which could be attributed to the synthetic terrain image application.

The mission was to fly in the low altitude block of 300 ft. to 500 ft. AGL while Terrain Masking through rugged terrain. It was hypothesized that synthetic terrain would allow the pilot to maintain a lower average altitude with less altitude variation over the course of the mission. It was also hypothesized that the pilot would maintain a higher average velocity and have less variation in speed using STI. Synthetic terrain was also expected to reduce deviation in pitch, sharp changes in pitch, and ground collision. A pilot's look time off-axis was expected to increase, reflecting the pilot's ability to "see" and consequently prepare for upcoming hill in the rugged terrain. It was hypothesized that when the pilot feels more comfortable and more in control of the situation (terrain proximity awareness) he would look off-axis longer to get "the feel" of the terrain around the aircraft as well as anticipating upcoming terrain changes.

In this segment of the evaluation four STI formats were compared to a baseline condition of no STI (HUD data only). Each pilot made five runs to perform the Terrain Masking task. The order in which the pilot made the runs, using the 5 different formats flying in either a northerly or southerly direction, was randomized over all pilots to balance any learning effects across the STI formats.

A counter-balanced design is presented in Table 3.

Table 3. A randomized experimental design matrix for the Terrain Masking runs

	Experiment Trials									
Pilot	1		2		3		4		5	
1	Grad	N	No STI	S	Ortho	N	Mesh	S	Points	N
2	Points	S	Ortho	N	No STI	S	Grad	N	Mesh	S
3	Mesh	N	No STI	S	Points	N	Grad	S	Ortho	N
4	Grad	S	No STI	N	Mesh	S	Points	N	Ortho	S
5	Grad	N	Ortho	S	No STI	N	Points	S	Mesh	N
6	Points	S	Ortho	N	Mesh	S	No STI	N	Grad	S
7	Ortho	N	Points	S	Mesh	N	Grad	S	No STI	N
8	Mesh	S	No STI	N	Ortho	S	Points	N	Grad	S
9	Grad	N	Ortho	S	Points	N	No STI	S	Mesh	N
10	Ortho	S	Grad	N	Points	S	Mesh	N	No STI	S

Similar to the Route Navigation task, the following data was collected during the course of each Terrain Masking exercise: aircraft altitude, speed, pitch, pilot's head azimuth, elevation. From this data, a number of metrics could be computed to measure pilot performance. Average altitude would indicate the pilot's ability to stay in the low altitude block. The integrated deviation in altitude was computed by the RMSE method where larger values indicate greater deviations in altitude along the flight path. Average speed would indicate the pilot's ability to maintain speed. The speed deviation would be computed as the integrated deviation by the RMSE method. Pitch deviation would also be computed as the integrated deviation by the RMSE method. Total look time off-axis and average look time off-axis would be captured. A count of sharp pitch changes and of ground collisions was also tallied on the Terrain Masking exercise.

Tests for statistical significance were computed using a 5 X 2 (format by direction) repeated measures analysis of variance (ANOVA) statistic for the average altitude, RMSE altitude, average speed, RMSE speed and RMSE pitch metrics with pilot, and STI format as factors in the analysis. A Chi Square statistic was used to test statistical significance of the frequency of sharp pitch changes and the frequency of ground collisions with pilot and STI format as factors.

5. Part-Task Evalution Results

Four engineering test pilots from Lockheed-Ft. Worth and 6 F-16 pilots from the US Air Force were used as subject pilots in the study.

Maj. Pete Demitry	AFTI/F-16 CTF 100 hrs F-16 (20 hrs AFTI) 650 hrs A-10 600 hrs F-4
Maj. Rick French	ACC/F-16 SPO 1600 hrs F-16A 200-300 hrs T-38
Maj. Mike Price	ACC/DOT 800 hrs F-16 Total (600 hrs LANTIRN) 900 hrs A-10 900 hrs T-37 IP
Capt. Chet Enigenberg	34FS Hill AFB 1200 hrs Total Military Aircraft 350 hrs F-16 C/D (20 hrs LANTIRN)
Capt. Jeff Nuccio	AFTI/CTF 800 hrs F-16 (300 hrs LANTIRN) 1000 hrs Night TF (F-16, F-111) 30 hrs AFTI HMD, 20 hrs NVG
Lt. Dave Twist	301 TFW 300 hrs F-16C 800 hrs F-4
Mr. Steve Barter	GD Flight Test 1400 hrs F-16 (30+ hrs Night)
Mr. Jon Beesley	GD Flight Test 800 hrs F-16 (120+ hrs Night) 20+ hrs F-22
Mr. Bland Smith	GD Flight Test 1300 hrs F-16 (10+ Night)
Mr. Steve Weatherspoon	GD/A-X Engineering 3100 hrs F-14 500 hrs Miscellaneous Aircraft

5.1 Subjective Format Assessment Summary. There was a general consensus that STI would be a benefit to low altitude operations. There was a preference indicated for the geographically fixed formats (i.e., points, points with ridgelines, mesh, tiles, and tiles & mesh. One draw back to the facility, which may have affected the results was the lack of an "outside window scene" off-axis. The only terrain representation was directly in front of the pilot, when looking off to the side the pilot could see the interior of the room housing the development station.

The highest ratings of operational utility came from the U.S. AIR FORCE participants in the study. The one rating of "Low Utility" from an Air Force participant was due to mechanization difficulties (update rate too slow at high sampling densities as well as tranmission delay because of competion for network resources).

Appendix A of the data book (separate deliverable) contains a blank subjective evaluation rating form. A complete compilation of the subjective comments is included in this report as Appendix B in the data book.

Figure 18 provides a summary of the subjective format assessment. The table is a summary of the subjective ratings obtained in Phases 3 and 4, reported below.

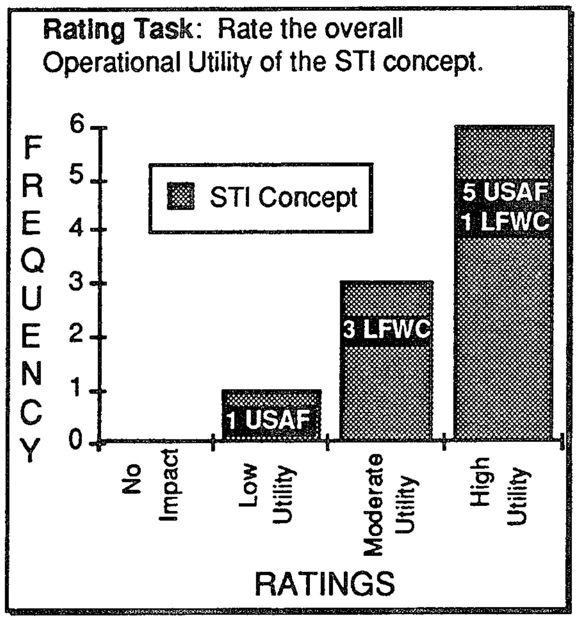


Figure 18
Overall Utility Rating for STI Concept

Table 4 summarizes the preference, utility and effectiveness rankings for the STI formats (A rating of "1" is best and "6" is worst).

Table 4. Summary of Subjective Ratings.

Subjective Data	Mesh	Turning Orthogonal	Rectangles	Points with Ridgelines	Gradient with Ridgelines	Gradient
- Preference Ranking	1.3	3.3	3.5	3.7	4.1	5.2
- Utility Rating (Rank Order)	1	2	3 *	3 * (* tie)	4	5
- Overall Effectiveness Ranking	2	1	3	4	5	6

5.1.1 Phase 1 (Sampling Density). A method of ascending and descending limits was used to systematically evaluate the preferred sampling density (100, 200, 400, and 800 meters). Pilots demonstrated a clear preference for the highest densities supported by the data base, see Figure 19.

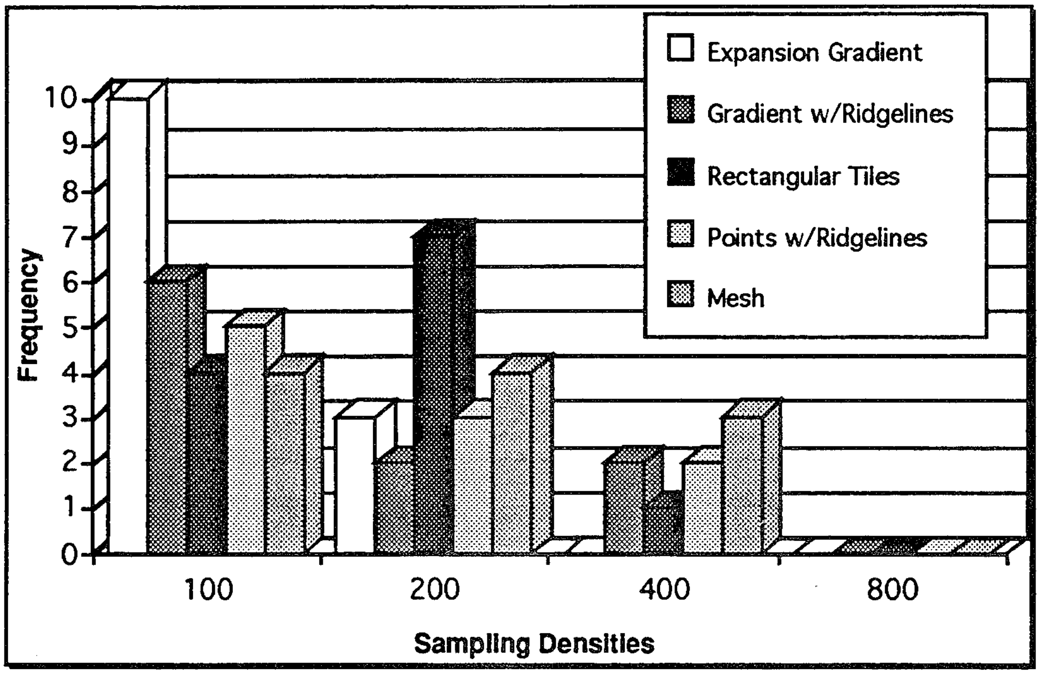


Figure 19
Sampling Density Preference for STI Formats

5.1.2 Phase 2 (Update Rate). As the sampling density was increased the computational and graphics throughput demands of the workstation increased as well so that maintaining a "satisfactory" update rate for refreshing the STI scene became a problem. In order to determine a value for minimum acceptable update rate, pilots were shown the Turning Orthogonal format at 5 different update rates (10, 15, 20, 25, and 30 Hz) and asked to indicate the minimum acceptable update rate. Figure 20 shows the results.

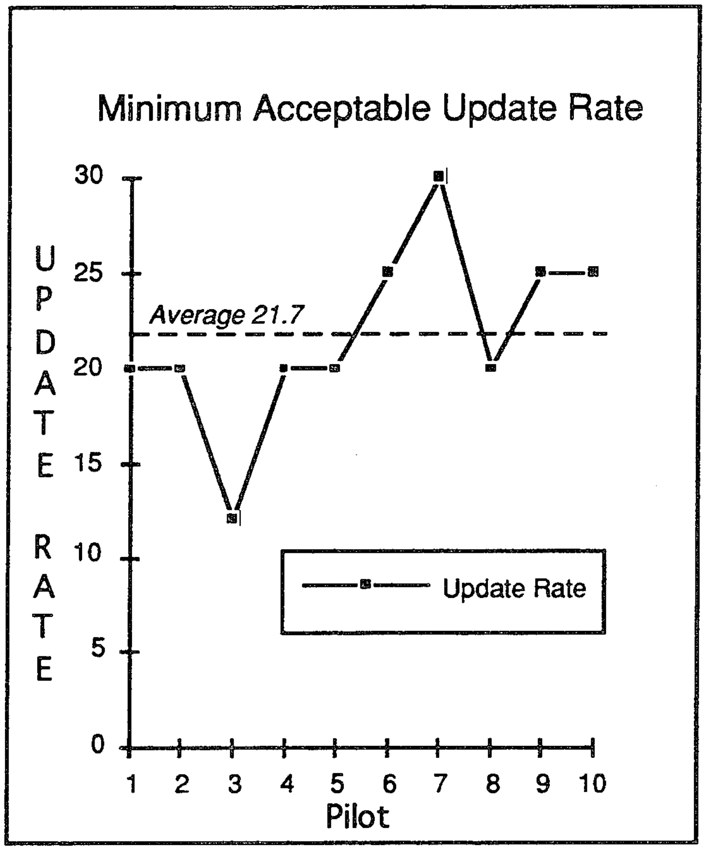


Figure 20
Minimum Acceptable Update Rate for Head-Centered STI Format

The average value for preferred update rate was 21.7 Hz, but the most frequently stated value as an acceptable update rate was 20 Hz (5 out of 10).

5.1.3 Phase 3 (Rank Order Format for Terrain Awareness). Pilots were asked to rank order the formats, from "best" to "worst," as to the ability to determine terrain awareness with the STI system.

Table 5. Individual Pilot Preference Ranking for STI Formats.

RANK ORDERING

Rank 1 (Best) through 6 (Worst)

	Mesh	Turning Orthogonal	Gradient w/ Ridgelines	Gradient	Points w/ Ridgelines	Rectangles
Pilot 1	[1]	[2]	[3]	[4]	[5]	[6]
Pilot 2	[1]	[2]	[5]	[6]	[3]	[4]
Pilot 3	[1]	[3]	[4]	[6]	[5]	[2]
Pilot 4	[1]	[3]	[2]	[4]	[6]	[5]
Pilot 5	[1]	[4]	[5]	[6]	[2]	[3]
Pilot 6	[1]	[2]	[5]	[6]	[3]	[4]
Pilot 7	[2]	[4]	[5]	[6]	[1]	[3]
Pilot 8	[2]	[6]	[3]	[5]	[4]	[1]
Pilot 9	[2]	[3]	[4]	[6]	[1]	[5]
Pilot 10	[1]	[4]	[5]	[3]	[6]	[2]

5.1.4 Phase 4 (Evaluation of Emergent Detail Concept). There was a general consensus that Emergent detail provides additional information regarding altitude because of the format changes at key altitude(s), see Figures 21 and 22.

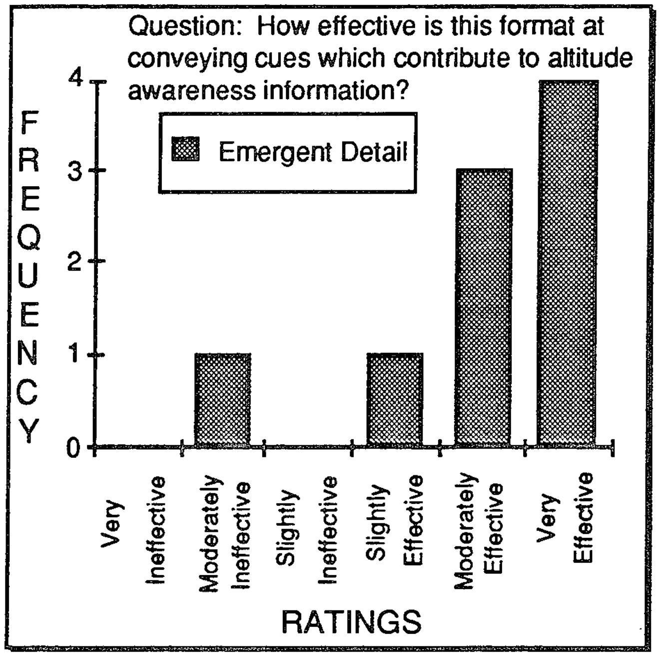


Figure 21
Altitude Awareness Effectiveness Ratings for Emergent Detail Concept

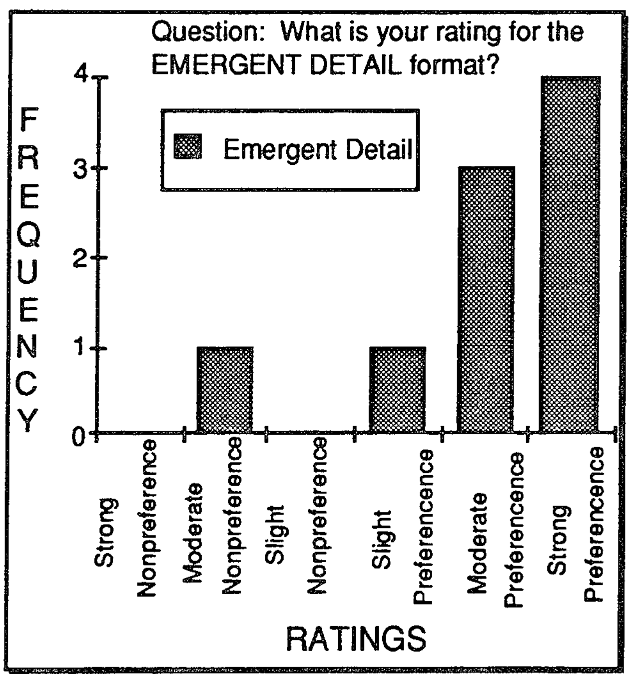


Figure 22
Preference Ratings for Emergent Detail Concept

5.1.5 Effectiveness & Utility Ratings. Figures 23 and 24 show the pilot's ratings for the effectiveness and utility of the various STI formats.

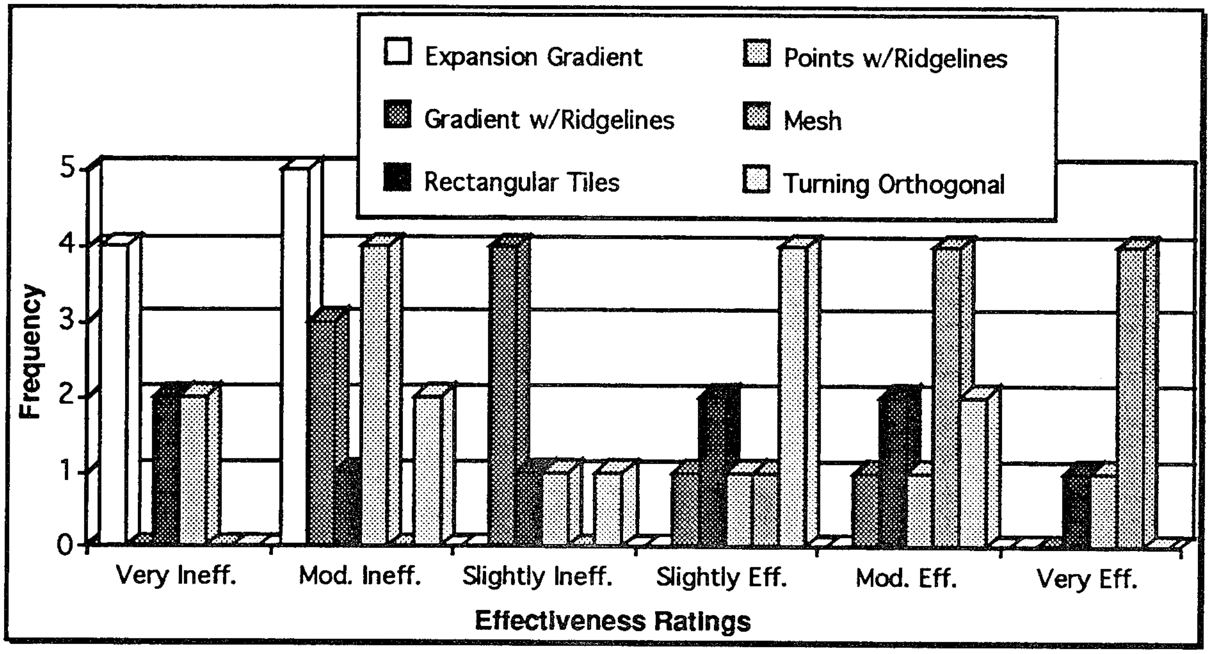


Figure 23
Altitude Awareness Effectiveness Ratings for STI Formats

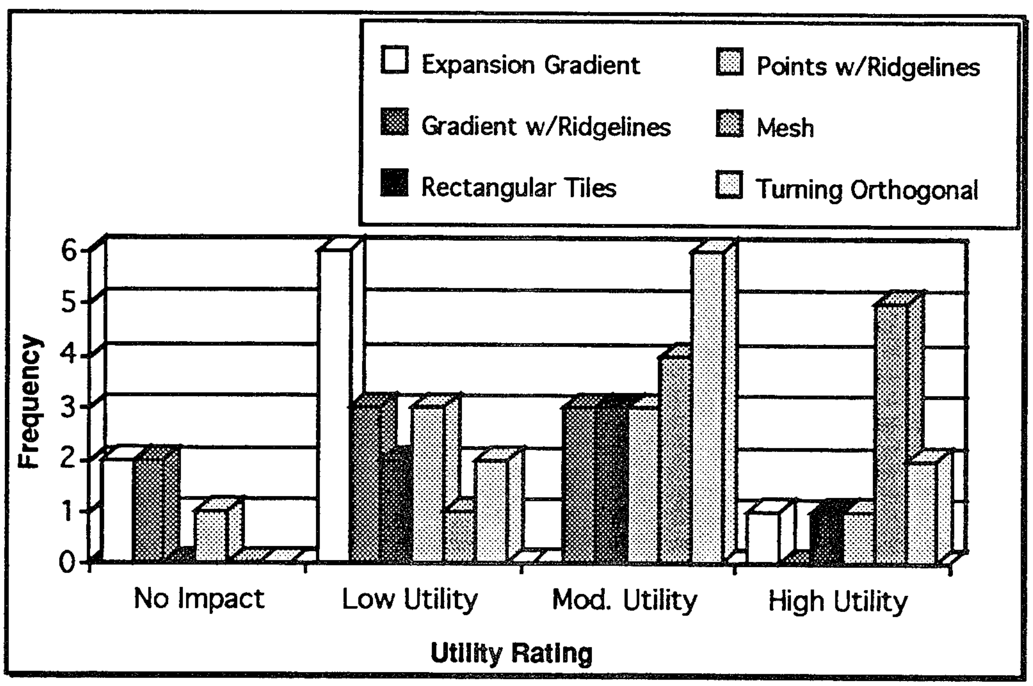


Figure 24
Utility Ratings for STI Formats

5.2 Route Navigation Flights. This evaluation measured the pilot's ability to fly fast at a low altitude, along a string of steerpoints, while following the Steering Cue in conjunction with the Flight Path Marker. Inferential statistics (Analysis of Variance and Chi Square) were used to determine if there was any difference in pilot performance between the HMD conditions (No STI and the various STI formats).

The performance data revealed very little in terms of an operational benefit gained from using STI for either the Route Navigation and Terrain Masking flights. This may have been the result of incorrect hypotheses, inappropriate metrics to test the hypotheses, the test was not conducted properly, the facilities were incapable of creating the desired test conditions, or any combination of the above reasons.

Of all the analyses conducted, only one significant effect was found. The pilot's ability to fly low was found to vary with STI formats, $F(4,46)=3.04$, MSe=27222.5 $p<.03$. An examination within the 5 format conditions showed a significant difference between No STI and Turning Orthogonal format, $F(1, 46)=11.44$, MSe=33176.5 $p<.01$, and the Turning Orthogonal and Points with Ridgelines formats, $F(1, 46)=4.99$, MSe=44695 $p<.03$, respectively. As can be seen from examining the values for Average Altitude in the table below the lowest flights were achieved without STI. The Turning Orthogonal format had the highest Average Altitude.

Table 6. Summary of Performance Data for Route Navigation Flights.

Route Navigation Flight Objective Data	No STI	Mesh	Turning Orthogonal	Points with Ridgelines	Gradient
Flight Performance					
- Average Altitude (ft. AGL)	470	559	604	544	539
- Average Velocity (KCAS)	528	531	527	536	517
- Average Pitch (deg.)	.013	.007	.060	.036	.020
- Average Time Off-axis (sec.)	2.1	2.2	2.4	2.5	2.4
- Average Time Pitch Danger	1.47	1.15	0.87	1.04	1.03
- RMS Altitude	9194	11428	12208	10123	9849
- RMS Velocity	443	240	225	201	175
- RMS Pitch	114	111	108	110	105
- Percent Time Off-axis	7.8	8.0	8.1	7.3	5.1
- Average Ground Strike(s)	.06	0	0	0	.13
Performance Variability					
- Std. Dev. of AVG. Altitude	86.8	142.4	124.9	162.8	120.2
- Std. Dev. of AVG. Velocity	23.3	35.1	27.3	32.8	16.3
- Std. Dev. of AVG. Pitch	.136	.149	.145	.139	.147
- Std. Dev. of RMS Altitude	3998	5853	4072	5154	4340
- Std. Dev. of RMS Velocity	1061	325	224	195	200
- Std. Dev. of RMS Pitch	39.3	40.1	29.7	19.9	27.6

A complete listing of the statistical analyses and averages for the various conditions is contained in Appendix C of the data book (separate deliverable).

After the pilots completed the Route Navigation flights they were asked to rate their preferred STI format for accomplishing those mission objectives. The Mesh format was preferred by 8 out of the 10 pilots, see Table 7.

Table 7. Most Preferred STI Format for Route Navigation Mission Requirements.

Route Navigation Flights

Question: What specific format(s) did you find most effective in conveying terrain awareness?

Pilot	Format
1	Mesh
2	Mesh
3	Mesh
4	Mesh
5	Mesh & Turning Orthogonal
6	Mesh & Turning Orthogonal
7	Turning Orthogonal
8	Gradient with ridgelines
9	Mesh & Points with ridgelines
10	Mesh

5.3 Terrain Masking Flights. This evaluation measured the pilot's ability to fly fast at a low altitude over rugged terrain. As was done with the Route Navigation flights, inferential statistics (Analysis of Variance and Chi Square) were used to determine if there was any difference in pilot performance between the HMD conditions (No STI and the various STI formats).

The only significant result found involving STI formats was for RMSE error in Velocity, $F(4,45)=4.39$, MSe=131609.4 $p<.01$). This curious result, since there is no "mission requirement" to change airspeed, is due to one run we consider an anomaly (Subject #6, using Points with Ridgelines STI format). Table 8 contains a summary of the performance data for the Terrain Masking flights.

Table 8. Summary of Performance Data for Terrain Masking Flights.

Terrain Masking Flight Objective Data	No STI	Mesh	Turning Orthogonal	Points with Ridgelines	Gradient
Flight Performance					
- Average Altitude (ft. AGL)	484	532	579	536	569
- Average Velocity (KCAS)	526	539	526	524	522
- Average Pitch (deg.)	-.100	-.067	-.160	-.010	-.044
- Average Time Off-axis (sec.)	1.9	2.2	1.6	2.4	2.0
- Average Time Pitch Danger	0.33	0.49	0.48	0.94	0.63
- RMS Altitude	5295	5323	6443	6257	6694
- RMS Velocity	28.2	7.0	12.4	283.2	98.0
- RMS Pitch	75.9	76.1	74.4	85.2	75.4
- Percent Time Off-axis	7.8	8.4	6.1	8.1	8.0
- Average Ground Strike(s)	.13	.22	.20	0	0
Performance Variability					
- Std. Dev. of AVG. Altitude	168.0	107.2	153.1	88.7	156.8
- Std. Dev. of AVG. Velocity	20.8	27.3	27.0	19.5	26.0
- Std. Dev. of AVG. Pitch	.438	.397	.344	.423	.394
- Std. Dev. of RMS Altitude	2976	1512	2958	2010	2683
- Std. Dev. of RMS Velocity	62	21	38	476	204
- Std. Dev. of RMS Pitch	25.9	16.8	18.8	30.8	19.7

A complete listing of the statistical analyses and averages for the various conditions is contained in Appendix D of the data book (separate deliverable).

After the pilots completed the Terrain Masking flights they were asked to rate their preferred STI format for accomplishing those mission objectives. The Mesh format was preferred by 9 out of the 10 pilots, see Table 9.

Table 9. Most Preferred STI Format for Terrain Masking Mission Requirements.

Terrain Masking Flights

Question: What specific format(s) did you find most effective in conveying terrain awareness?

Pilot	Format
1	Mesh
2	Mesh & Turning Orthogonal
3	Mesh < 1000 ft / Ortho > 1000 ft
4	Mesh
5	Mesh
6	Mesh
7	NONE!
8	Mesh
9	Mesh
10	Mesh

6. Part-Task Simulation Conclusions & Recommendations

STI was subjectively rated as beneficial by the pilots participating in the Part-Task simulation study. A niche for STI is developing as the program proceeds, namely STI can fill in the visual "gaps" in a low visibility (or night) attack weapon system by providing off-axis terrain cues as well as filling in the forward visual scene under degraded FLIR operating conditions.

6.1 Full Mission (Dome) STI Improvements.

The following is a list of general conclusions:

- To provide depth perception and make the pilot comfortable at low altitudes, STI needs to display features close to the aircraft. Very important when descending to low altitudes, so it does not appear like descending into a black hole.
- Ridgelines (or lines perpendicular to aircraft heading) are always needed, even if the terrain is flat.
- <u>All</u> ridgelines need to be drawn. (During this simulation, some ridgelines close to the F-16 were not drawn.)
- The minimum acceptable update rate is between 20-25 Hz, based on pilots' ratings.
- Emergent detail is moderately to very effective at contributing to attitude awareness.
- The Geographically Fixed reference system is preferred by all of the pilots.
- The amount of synthetic imagery desired depends on where and why it is being used.
  - If STI is to enhance the FLIR image, pilots want less detail because they do not want it to obscure the FLIR image. This is where the Points with Ridgelines may be the most useful.
  - If/when the pilot is looking into an area with no FLIR (i.e., Off-Axis), the pilots prefer more detail because nothing is being obscured.
- A hands-on switch to turn STI ON/OFF is needed.
- Sampling the terrain only at set distances could be dangerous. Peaks in-between sampling locations could be missed (i.e., need to show the highest elevation within the sampled area, even when 100m spacing used). This would require using a DMA data base with higher sampling density to computationally determine peaks within the 100 m spacing so that some form of graphic could display the hazardous nature of the terrain *hidden* by the spacing artifact.
- Over flat terrain, there are too many lines/points on the horizon.

6.2 Recommendations.

The Full Mission simulation will be used to test STI as acomplimentary system to LANTIRN. STI will be tested under "good" and "bad" FLIR conditions. The utility of ridgelines will be tested as an enhancement of the forward field-of-view.

6.2.1 Mission Instructions. The lack of systematic effects in piloting performance, either improvements or decrements, is attributed to the instructions to fly a block altitude as well as an altitude alerting mechanization in the F-16 cockpit that warns the pilot if he has deviated from the altitude block. To determine the influence of STI on pilot's comfort with low level flight, and subsequent performance changes, in the Full-Mission simulation pilots will be instructed to fly as "low as they feel comfortable."

6.2.2 Down select of STI Formats. The Mesh and Turning orthogonal formats will be used, as well as a new mechanization of the Emergent Detail concept that fills in the gaps that occurs when the lines rendered in these nominal formats suffer from splay at extremely low altitudes, under 500 ft. AGL.

6.2.3 STI Mechanization. A hands-on throttle and stick (HOTAS) switch to turn STI ON/OFF is needed. In keeping with the design philosophy of providing the pilot with total system control, while maintaining control of aircraft attitude and thrust, an implementation that allows for the control of STI presentation is warranted.

7. Full Mission (Dome) Simulation

7.1 Full Mission Simulation Objective. The overall objective of the full mission simulation was to assess the benefit STI provides a LANTIRN-equipped Block 40 F-16 aircraft performing a night attack mission. It was assumed that STI will increase the probability of mission success by enhancing spatial orientation and terrain awareness while flying at low altitude. This should be accomplished in two ways. First, the STI image, displayed on the HMD, will show a terrain image outside the HUD field-of-view. The pilot will now be able to look off-axis into a turn to select the best route of flight for terrain masking, threat avoidance or offensive positioning. With STI the pilot will also have the capability to tactically maneuver the aircraft at low altitude in all weather conditions. Secondly, STI should provide a terrain image that augments the NAV FLIR image in the HUD under conditions when an IR image is marginal or unavailable due to low visibility, high humidity or low thermal contrast.

Therefore, global mission effectiveness was evaluated along two dimensions:

- Enhancements to successful weapon delivery (Lethality).
- Improvements in Survivability, both in terms of Pilotage and Threat Reaction.

In order to assess the impact of STI on mission effectiveness a number of operational factors were manipulated. These factors were the type of STI format used (None, Points with Ridgelines, and Mesh), terrain profile along route (flat and rugged), and FLIR image quality presented in the HUD from the LANTIRN system (good and poor). Each pilot was exposed to each simulation condition in a 3 X 2 X 2 repeated measures design.

Threats, in the form of surface-to-air missiles, were present during the missions flown.

The remainder of this report will detail the full mission simulation portion of this study.

7.2 Dome Simulation Facility Description. The full mission portion of the STI study was conducted in the 24 foot Dome #1 in the LFWC Flight Simulation Laboratory (FSL). The Dome simulation environment provides a high fidelity visual scene projected 360° around the pilot. The cockpit was an F-16 Block 40 configuration which included the Honeywell Helmet Mounted Display (HMD), a Wide Angle Raster (WAR) HUD and LANTIRN capability to include auto terrain following (use of auto terrain following was left to the pilot's discretion during this evaluation).

Briefing Room B was used throughout the simulation for mechanization review, mission briefings, debriefings and general discussion. Video monitors in the FSL observation area showed all cockpit displays as well as a mission overview which allowed observers to monitor mission progress. The FSL and the rooms mentioned above are depicted in Figure 25.

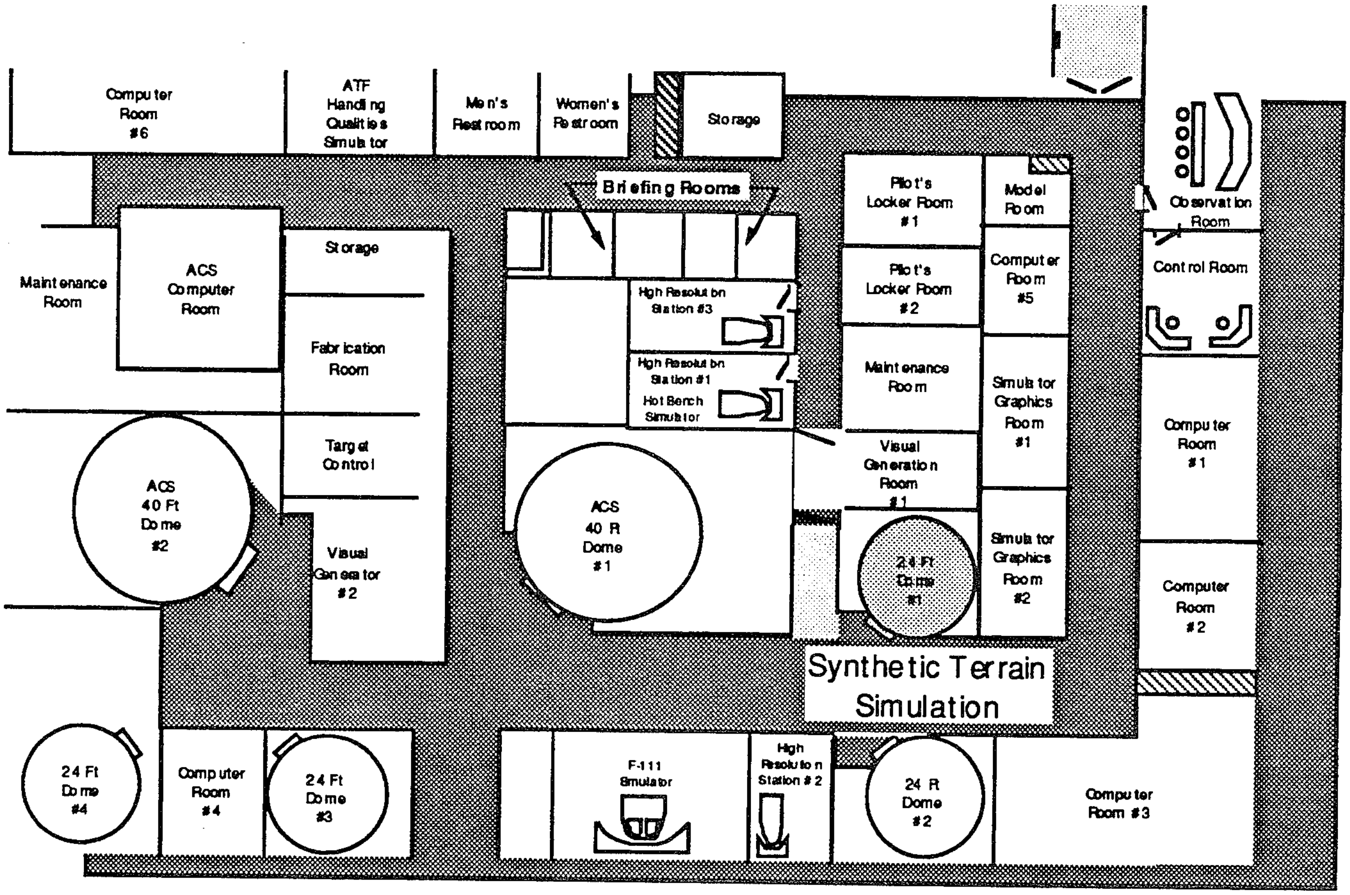


Figure 25
Flight Simulation Laboratory

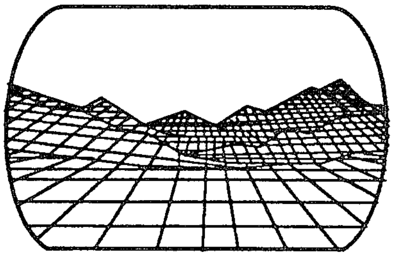
7.3 STI System Mechanization. Based on the general conclusions outlined in Section , two formats were carried forward and evaluated in the full mission simulation. These were Points with Ridgelines and Mesh, shown in the figure below.

The STI format was displayed in the HMD when looking off-axis. As the pilot looked forward, within the HUD field-of-view, the STI format was controlled using the manual range knob on the throttle. For example, with the knob rotated counterclockwise there was no STI, rotating to the mid-detent, ridgelines were shown, rotating full clockwise displayed full STI. The outside FLIR image was always displayed in the HUD field-of-view.

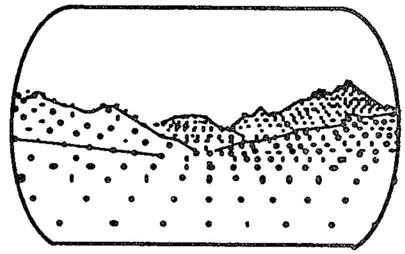
Selecting the NO STI option on the Data Entry Display inhibited STI both on- and off-axis.

7.3.1 Points with Ridgelines. This geographically centered format lights each sample point in the data base at the appropriate elevation. Ridgelines are drawn where the terrain slope parallels the line of sight. The rendering approach for this format is discussed in Section 3.2.2.2.

7.3.2 Mesh. This geographically fixed presentation scheme looks as though a large net were laid across the earth. The grid is deformed by topographic surface features. The rendering approach for this format is discussed in Section 3.2.2.3.



Mesh



Points with Ridgelines

7.4 Mission Scenarios. The pilots participating in this study flew four different profiles:

- Familiarization Profile
- "Flat" Terrain Profile
- "Rugged" Terrain Profile
- Combat Run

The pilot's used conventional steering cues (Flight Path Marker) and waypoint data in the HUD to follow the briefed route.

7.4.1 Familiarization Profile. The initial profile was a training profile that was very simple and allowed the pilot to become familiar with switchology, the Helmet Mounted Display (HMD), and the different terrain formats that were to be evaluated. Here the pilot was able to fly at low altitude, request varying FLIR conditions, practice avoiding threats and employing a variety of weapons. Once the pilot became comfortable using the HMD and associated STI formats, data collection runs began.

7.4.2 Flat and Rugged Terrain Route Profiles. Two common profiles were used for the data collection runs. These two profiles consisted of a "mild terrain" profile where the terrain was a minimal factor in the execution of the mission and a "rugged terrain" profile where the pilot was tasked with execution of the mission while utilizing and avoiding rapidly changing terrain elevations.

There are two notable differences between the two terrain profiles. First, the ordinance used in the Flat profile is a laser guided bomb and in the rugged route Mk-82 iron bombs are used. Second, the rugged route, with iron bombs, allows for an off-set reattack of the target (see Figure 26). The actual routes are shown on the following pages.

It is important to note that only the Rugged route, with the Mk-82 ordinance, utilized a reattack scenario.

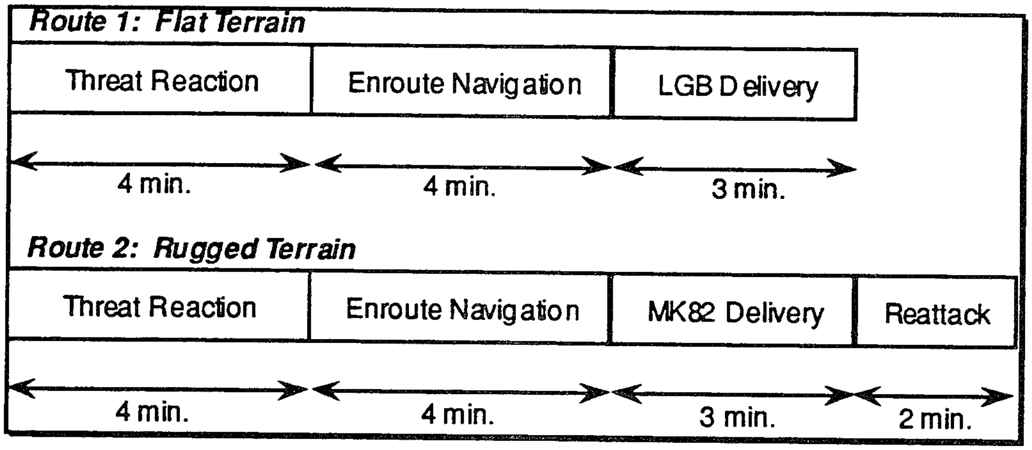


Figure 26
Two Routes used in Dome Simulation

7.4.2.1 Threat Reaction. During the initial segment of the run the pilots were exposed to the threat of surface-to-air (SA) missile launch. The types of missiles threats, and the corresponding launch parameters are shown below:

Type	ActiveRg (nm)	MaxLaunch (nm)	MinLaunch (nm)	MinEL (deg)	MaxEL (deg)	MaxAlt (ft)
SA-2	31.5	21.0	4.0	2.0	75.0	30000
SA-3	15.0	10.0	1.7	0.5	75.0	40000
SA-4	52.5	35.0	4.0	2.0	75.0	35000
SA-6	15.0	10.0	1.0	2.3	45.0	25000
SA-8	10.5	7.0	1.0	4.6	72.0	19000

ActiveRg : Range at which the site's radar can acquire.
MaxLaunch : Maximum range at which a launch might occur.
MinLaunch : Minimum range at which a launch might occur.
MinEL : Minimum elevation of the ownship above the threat site for acquisition and launch.
MaxEL : Maximum elevation of the ownship above the threat site for acquisition and launch.
MaxAlt : Maximum altitude of the ownship above the threat site for acquisition and launch.

A radar warning receiver was utilized to inform the crew of missile launch detection. There are a number of factors that contribute to the success of breaking missile lock. The aircraft must maneuver in response to a missile warning to succeed in breaking missile launch. If the aircraft pulls 3.5 G for at least two seconds, it is considered to be Maneuvering. In addition, the expenditure of chaff will help defeat the missile. Chaff is effective for two seconds after release. The formula used to calculate breaklock follows:

Probability of Breaklock =
G_Weight * Ownship_Gs_Above_3.5 +
ECM_Pod_Effects +
Chaff_Effects +
G_Effects

G_Weight = 0.01 for a PD radar
= 0.05 for a non-PD radar

Ownship_Gs_Above_3.5 = Total Gs - 3.5

ECM_Pod_Effects = 0.2 vs PD radars
= 0.35 vs non-PD radars

Chaff_Effects = 0.7 vs all non-PD radars, regardless of Maneuver
= 0.35 vs PD radars, on the beam, non-Maneuvering
= 0.7 vs PD radars, on the beam, Maneuvering
= 0.05 vs PD radars, off the beam, non-Maneuvering
= 0.1 for PD radars, off the beam, Maneuvering

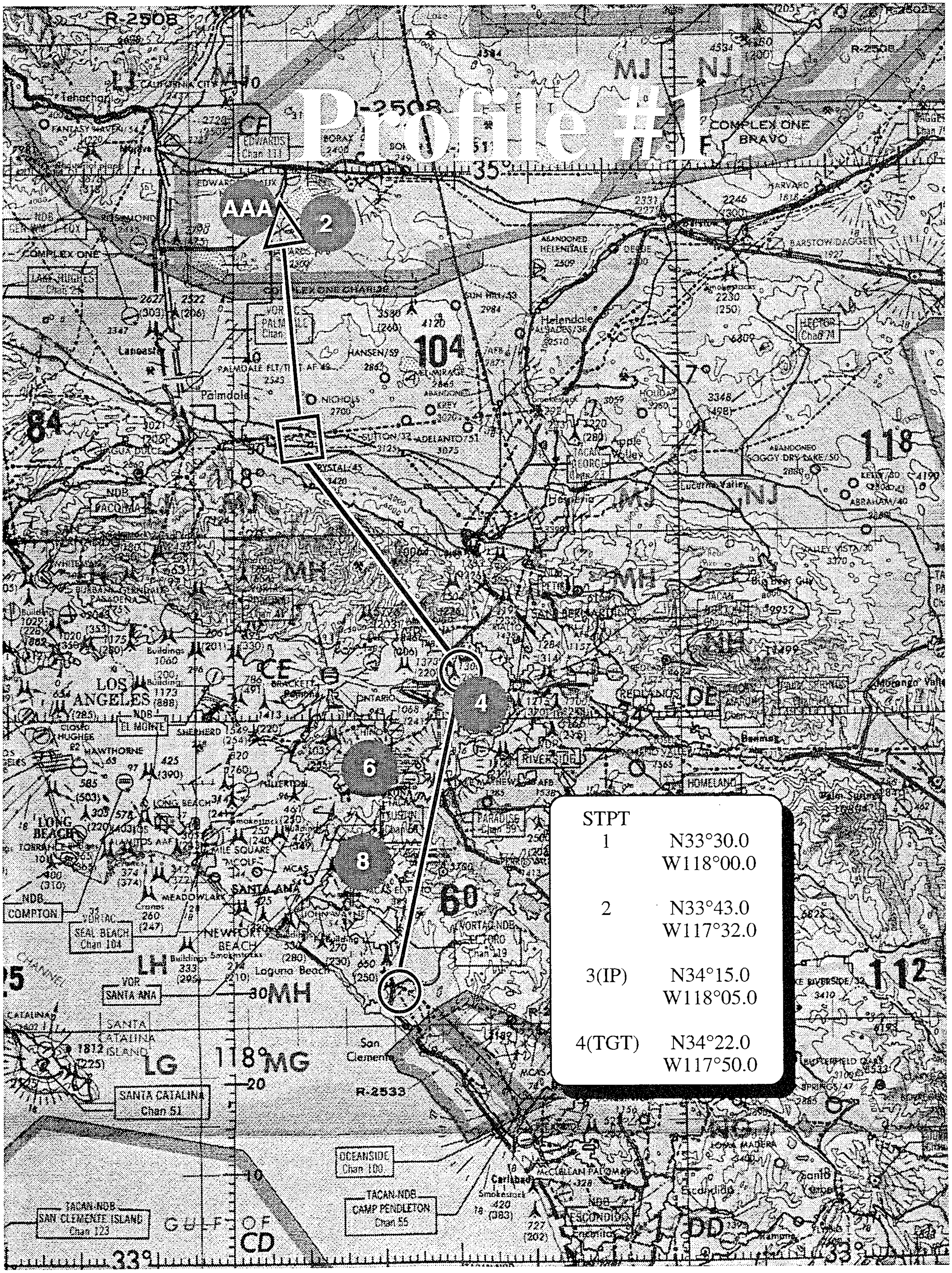
G_Effects = 0.2 if a Maneuver has occurred

Breaklock is checked whenever Breaklock Probability changes.

7.4.2.2 En Route Navigation. During this portion of the route the SA missile threat was removed and pilots were instructed to continue following the briefed route making maximum use of terrain masking tactics.

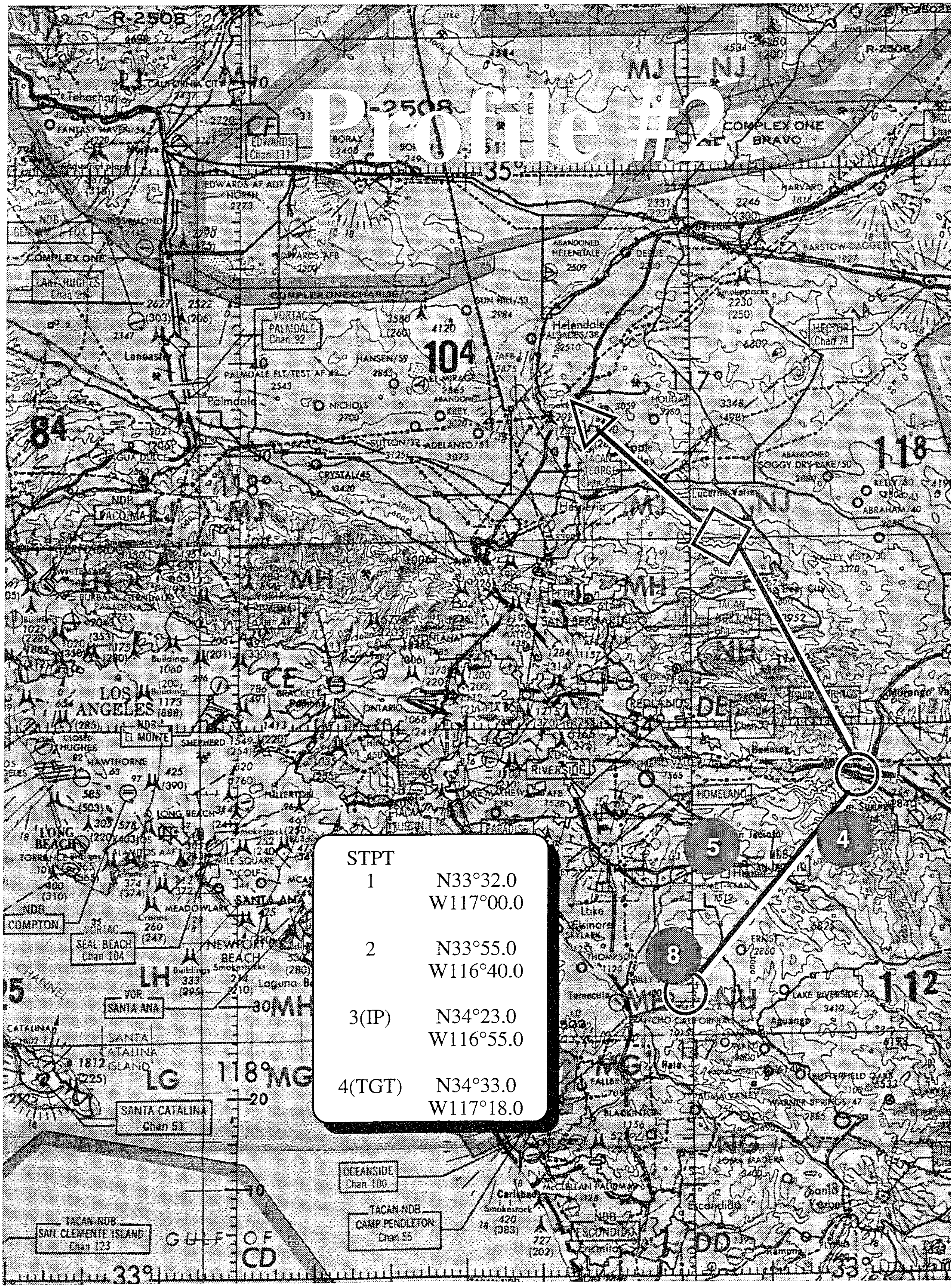
7.4.2.3 Weapon Delivery and Reattack. This portion of the route was defined as passage of the Intialization Point (IP) through weapon delivery until established within $\pm 3^\circ$ of egress heading. For the initial attack run on the target a straight ahead delivery tactic was employed. For the reattack, for the Rugged Route trials, an offset delivery method was used.

Profile #1



STPT	
1	N33°30.0 W118°00.0
2	N33°43.0 W117°32.0
3(IP)	N34°15.0 W118°05.0
4(TGT)	N34°22.0 W117°50.0

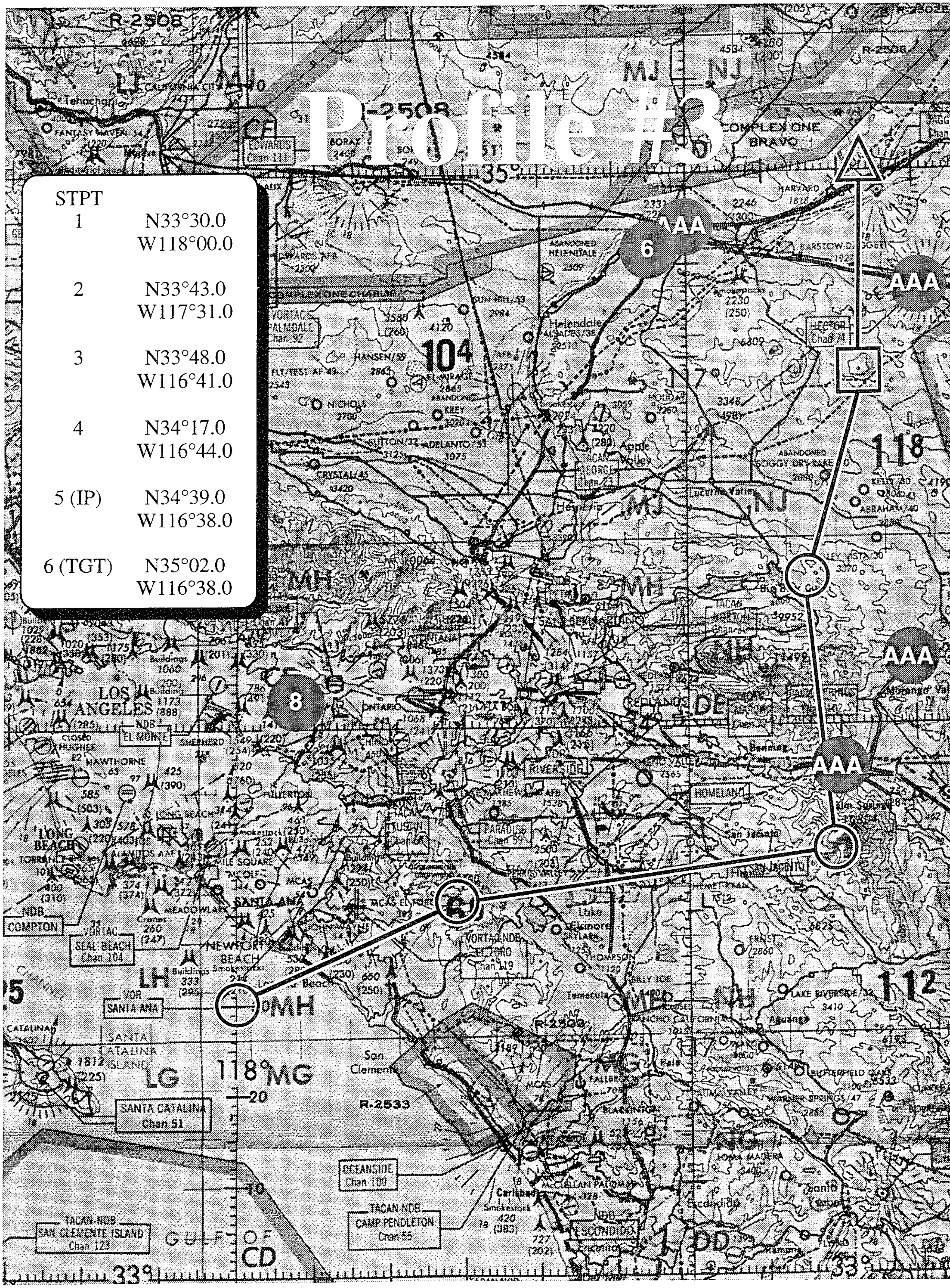
Profile #2



STPT	
1	N33°32.0 W117°00.0
2	N33°55.0 W116°40.0
3(IP)	N34°23.0 W116°55.0
4(TGT)	N34°33.0 W117°18.0

7.4.3 Combat Run. The last mission was a combat scenario in which the pilot could choose a desired STI format (Mesh, Points with Ridgelines or no STI). The mission began with the aircraft above an undercast. The pilot had to descend through the weather to VMC at low altitude. Enroute weather was expected to be 5500/3. The mission objective was to destroy a preplanned target. The pilot was given a preplanned low level route to the target but he could deviate as necessary to make his assigned time-on-target. The pilot was also told to fly as realistically as possible and to abort the mission if weather became a factor. Numerous SA-6, SA-8, SA-2 and SA-4's were located enroute to the target area as well as airborne MiG-29's.

Profile #3



STPT	
1	N33°30.0 W118°00.0
2	N33°43.0 W117°31.0
3	N33°48.0 W116°41.0
4	N34°17.0 W116°44.0
5 (IP)	N34°39.0 W116°38.0
6 (TGT)	N35°02.0 W116°38.0

7.5 LANTIRN FLIR Image Quality. Another factor which can effect the utility of STI would be the forward terrain image quality provided to the HUD by the LANTIRN system. A good IR condition was defined in this study to be when the IR sensor could see beyond the display of the synthetic terrain (outside of 6 NM). Poor IR conditions were defined as visibility less than 6 NM.

7.6 Experimental Design. One of the major tasks of this Synthetic Terrain Imaging Simulation was to acquire and analyze objective and subjective pilot performance data to determine potential operational benefits of an STI system. Experiments were designed to assess pilot performance and mission effectiveness of the STI candidates. Objective performance data were collected using mission scenarios that provided a realistic operational environment. Table 10 depicts the experimental design and presentation order for each STI Format, pilot, route and FLIR condition. In conjunction with the objective data collected, questionnaires and extensive debriefings after each data run were used to collect subjective data. Specific questions were asked to determine desirable mechanization/STI implementation as well as evaluating overall operational utility of the system.

Table 10. A randomized experimental design matrix for Full Mission Simulation

	Pilot					
Exp. Trials	1	2	3	4	5	6
(1)	$S_1F_1R_2$	$S_1F_2R_2$	$S_3F_1R_1$	$S_1F_1R_2$	$S_3F_2R_2$	$S_3F_2R_1$
(2)	$S_2F_1R_1$	$S_2F_2R_1$	$S_1F_2R_1$	$S_2F_2R_2$	$S_1F_2R_2$	$S_2F_1R_1$
(3)	$S_2F_2R_1$	$S_3F_1R_1$	$S_3F_2R_1$	$S_3F_1R_1$	$S_1F_1R_1$	$S_2F_1R_2$
(4)	$S_3F_1R_1$	$S_1F_2R_1$	$S_2F_1R_1$	$S_2F_2R_1$	$S_3F_1R_2$	$S_1F_2R_1$
(5)	$S_3F_2R_1$	$S_3F_2R_1$	$S_1F_2R_2$	$S_2F_1R_1$	$S_2F_1R_2$	$S_3F_1R_1$
(6)	$S_3F_1R_2$	$S_2F_1R_1$	$S_3F_2R_2$	$S_3F_1R_2$	$S_3F_2R_1$	$S_1F_1R_1$
(7)	$S_2F_1R_2$	$S_1F_1R_1$	$S_3F_1R_2$	$S_2F_2R_2$	$S_2F_1R_1$	$S_3F_2R_2$
(8)	$S_1F_2R_2$	$S_2F_1R_2$	$S_2F_2R_1$	$S_3F_2R_1$	$S_1F_1R_2$	$S_2F_2R_1$
(9)	$S_1F_1R_1$	$S_1F_1R_2$	$S_1F_1R_1$	$S_1F_2R_2$	$S_2F_2R_2$	$S_1F_2R_2$
(10)	$S_1F_2R_1$	$S_2F_2R_2$	$S_2F_1R_2$	$S_3F_2R_2$	$S_1F_2R_1$	$S_2F_2R_2$
(11)	$S_2F_2R_2$	$S_3F_2R_2$	$S_1F_1R_2$	$S_1F_1R_1$	$S_2F_2R_1$	$S_3F_1R_2$
(12)	$S_3F_2R_2$	$S_3F_1R_2$	$S_2F_2R_2$	$S_1F_2R_1$	$S_3F_1R_1$	$S_1F_1R_2$

7.7 Data Collection. A total of three STI conditions (No STI, Points with Ridgelines and Mesh) were evaluated. Both subjective and objective data was collected during the full mission simulation assessment of STI on mission effectiveness.

Subjective data consisted of assessing pilot preference for each STI format with respect to improving operational utility, while providing real time route deviation capability for terrain masking to avoid threats.

Objective data was used to quantify performance improvements attributed to the addition of the STI formats. For each route segment the following hypothesis and associated measures of merit were assumed:

7.7.1 Predicted Improvements in Mission Effectiveness. As mentioned in the beginning of this section, it was anticipated that STI would improve overall mission effectiveness in theareas of improved weapon delivery and survivability. The following are specific operationalizations for those predicitions.

Improved Weapon Delivery

- Lower average altitude flown in the target area, both initial attack and reattack, with STI
- Lower time to reattack with STI
- Smaller distance flown off target before reattack with STI
- Greater time spent gazing off-axis for target acquisition with STI
- Higher percentage of successful weapon deliveries with STI

Improved Survivability

Pilotage

- Fewer Controlled-Flight-Into-Terrain incidents with STI
- Lower average altitude with STI
- Less variability in altitude with STI
- Lower maximum terrain height overflown with STI
- Greater average deviation between average altitude and MEA with STI (terrain masking tactics)
- Greater average velocity with STI
- Greater percentage of time flown in IFR weather conditions with STI

Threat Reaction

- Lower average altitude in area with SAM threat with STI
- Greater average G loading (maneuvering agressiveness) in response to missile launch with STI
- Fewer SAMs launched at aircraft with STI
- Greater percentage of SAM defeats with STI

Weapon Delivery

- Lower time to establish egress heading with STI

8.0 Full Mission Simulation Results

Six F-16 pilots from the US Air Force were used as subject pilots in the study.

Lt. Col. John Wagner	310 FS Luke AFB 600 hrs F-16 BLK 40 1400 hrs F-4 900 hrs T-38
Maj. Mike Price	ACC/DOTO-T 900 hrs F-16 (600 hrs LANTIRN) 900 hrs A-10 900 hrs T-37
Capt. Scott Coleman	310 FS Luke AFB 1250 hrs F-16
Capt. Gary Guy	307 FS Moody AFB 350 hrs F-16 BLK 30 150 hrs F-16 BLK 40
Capt. Mike Sindel	363 OG/OGV Shaw AFB 1400 hrs F-16
Capt. Paul Wilder	19 FS Shaw AFB 1700 hrs F-16

This section summarizes the subjective and objective results from the full mission simulation. Volume 2 of this report contains the subjective questionnaire responses and analyses of the objective results.

8.1 Limited Result Interpretation. The ability to interpret simulation results as being representative of real-world operations is always subject to a "leap of faith." In the current study we were attempting to assess the effect STI in a Helmet-Mounted Display would have on the pilot's ability to maneuver agressively during low level flight, yet in the simulator the pilot would not experience the G loading associated with agressive manuevers. There were two simulation specific issues associated with the present simulation that limit the interpretation of the results of this effort.

8.1.1 Misregistration of STI and Dome Scene. One major limitation of the full mission simulation portion of this study was a misalignment of the synthetic terrain image to the outside visual scene projected onto the dome. In some places the alignment was negligible, while in other places the elevation of the STI image could be misregistered by as much as ± 300 feet. The misalignment arose because of the curved-earth simulator visual scene versus a flat-earth projection algorithm for synthetic terrain. The misregistration was most notable in the rugged terrain condition when prominent terrain features were visible.

The pilots were asked if the misregistration had an impact on what they were doing, most indicated it did (Pilot #6 did not answer), see Figure 27.

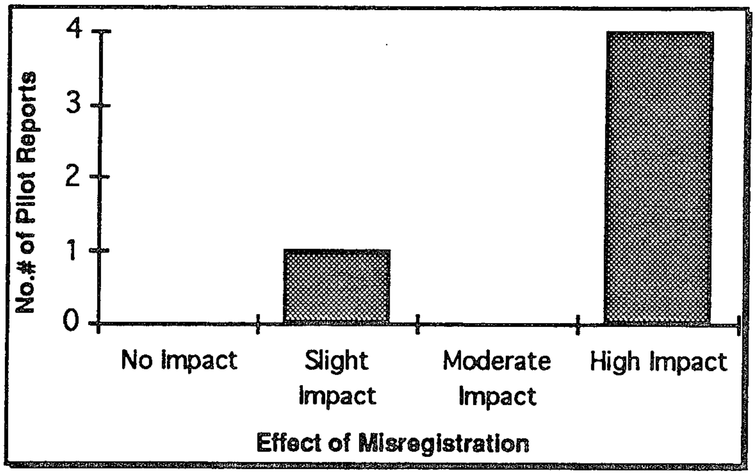


Figure 27
Impact of Misregistration on STI Usability

To determine if the consequences of the misregistration were negative the pilots were asked if the misregistration distracted or irritated them. The pilots were unanimous in stating the misregistration was distracting and irritating (Pilot #6 did not answer), see Figure 28.

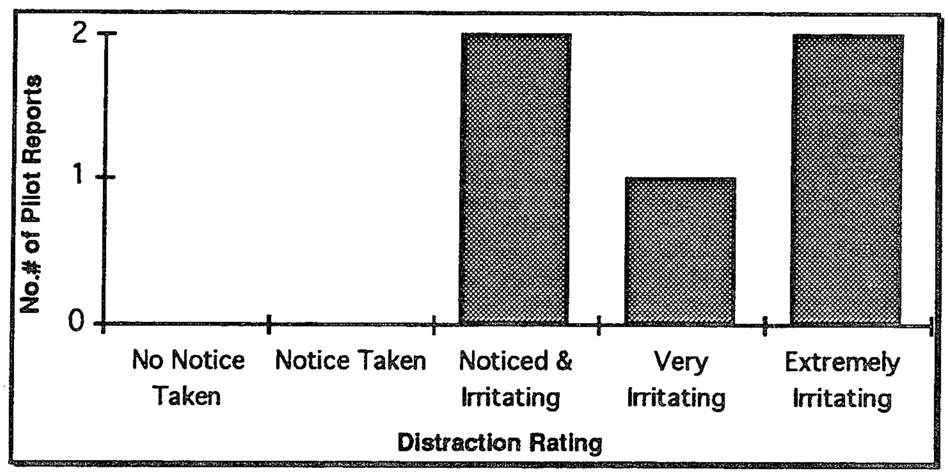


Figure 28
Irritation/Distraction Ratings for STI Misregistration

This misregistration problem was corrected subsequent to the simulation.

8.1.2 Faulty Weather Modelling. Another limitation was the inability to effectively simulate weather conditions. For example, as the pilot penetrated a cloud layer the visibility was intended to slowly degrade to zero. Instead, the visibility went from VFR above the clouds to 0/0 in the clouds and then VFR under the clouds. Even with this limitation we were still able to assess the ability to use STI during IMC conditions.

8.2 Subjective Results. Overall, the concept of synthetic terrain appears to be a usable approach for providing the pilot off-axis terrain features. During the simulation each pilot was instructed to evaluate the concept of STI and not dwell on the misalignment problem. As previously mentioned, the synthetic image did not always match the outside visual scene but most pilots were able to overlook this problem and make valuable conclusions/recommendations for utilizing synthetic terrain imagery. For example, most agreed that presenting synthetic terrain in an HMD would be a very useful concept for allowing off-axis viewing of the surrounding terrain, greatly improving situational awareness. Overall, synthetic terrain imagery has the potential to improve night mission performance under poor weather conditions. As reported by the pilots, textured contours would greatly improve the usability of the HMD image.

8.2.1 Weapon Delivery. The LANTIRN implementation requires all targeting to be done with the intended target directly in front of the aircraft (± 10°off boresight). STI allows for visual acquisition of the target and surrounding terrain when the intended target is *not* directly in front of the aircraft.

Pilots indicated that STI was not an improvement over the LANTIRN implementation in terms of providing altitude information, but was beneficial for off-axis targeting and reattack (another off-axis weapon delivery maneuver).

The pilot's subjective ratings indicate that there was no gain in *Altitude Information during an Ingress to a Target Area* with the use of either STI format over a conventional LANTIRN implementation (Figure 29). It should be noted that the Very Ineffective ratings for STI came from one pilot.

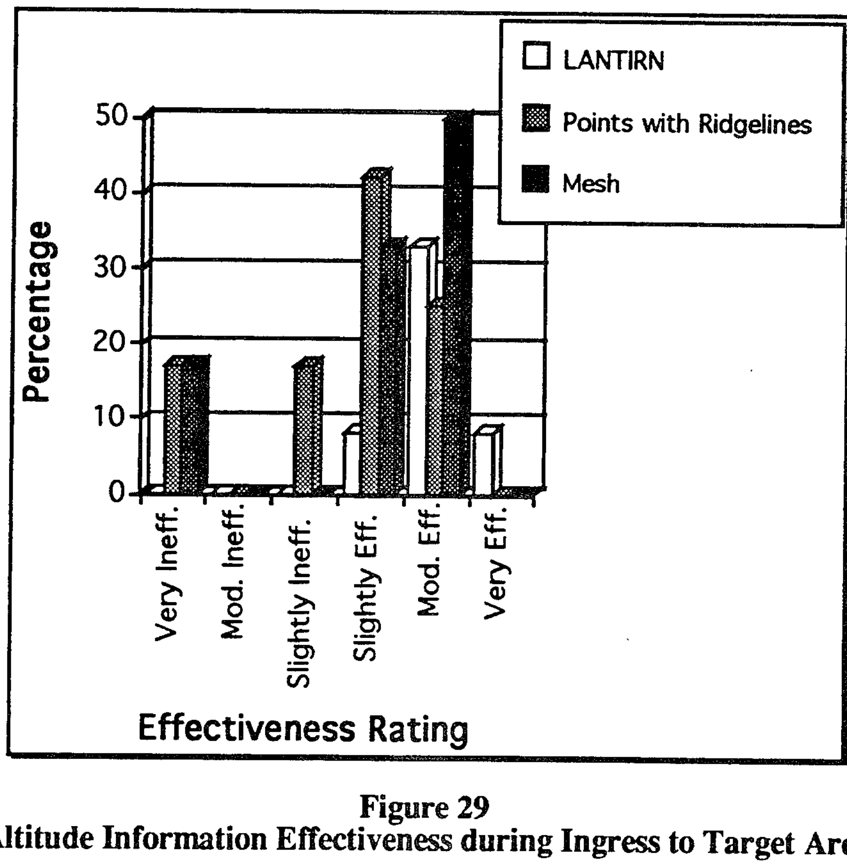


Figure 29
Altitude Information Effectiveness during Ingress to Target Area

The pilot's subjective ratings indicate that there was a gain in *Off-Axis Weapon Delivery Effectiveness* with the use of either STI format over a conventional LANTIRN implementation (Figure 30). This ordinance delivery technique was only applicable to the release of Mk-82's on the rugged profile.

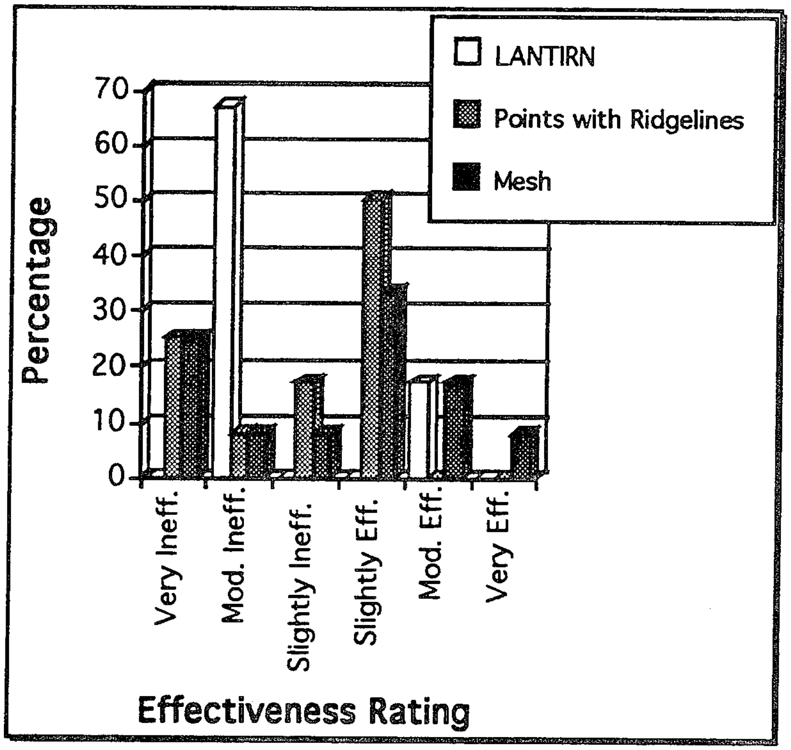


Figure 30
Off-Axis Weapon Delivery Effectiveness
(Rugged Route Profile *only*)

The pilot's subjective ratings indicate that there was a marked gain in *Reattack Effectiveness* with the use of either STI format over a conventional LANTIRN implementation (Figure 31). As mentioned earlier, the reattack maneuver was only utilized in the rugged terrain profile, when the pilots were releasing Mk-82 ordinance.

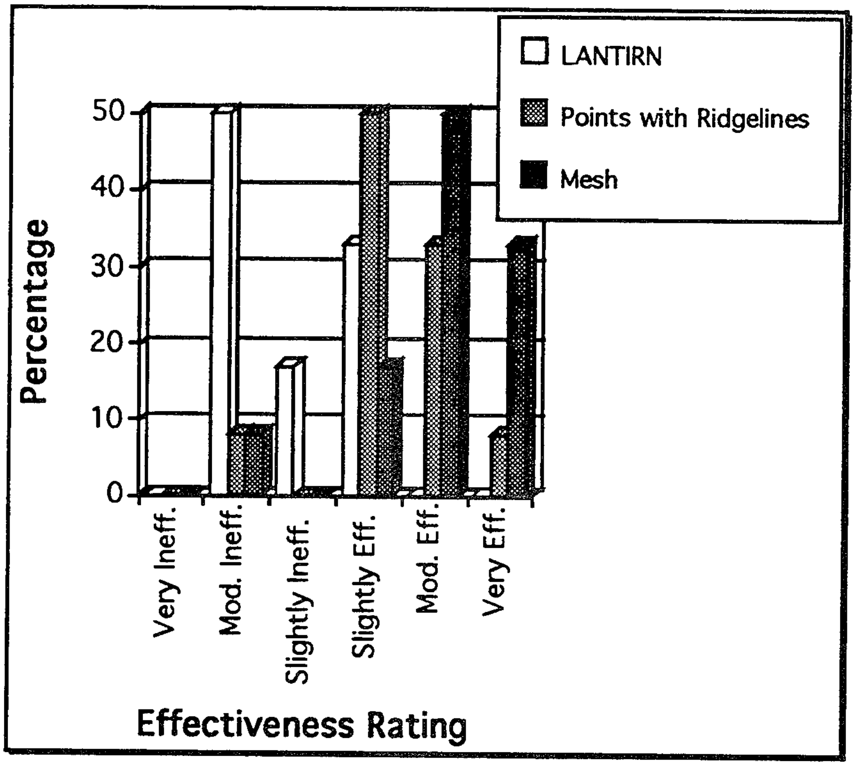


Figure 31
Reattack Effectiveness
(Rugged Route Profile *only*)

8.2.2 Survivability – Pilotage. Another operational benefit to be derived from STI is in terms of safety, by providing the pilot with terrain proximity awareness during low level flight. Terrain proximity awareness will allow the pilot to fly lower more comfortably. In addition, the ability to look outside the LANTIRN field-of-view (±14° horizontal and ±10.5° vertical) allows the pilot to select routes that provide for better terrain masking.

8.2.2.1 Altitude Information. A key to surviving flight into hostile airspace is the ability to fly low to avoid detection. To determine if there was an operational gain over LANTIRN by using STI the pilot's were asked Altitude Information Effectiveness and Confidence in Low Level Flight.

The pilot's subjective ratings indicate that there was no gain in *Overall Altitude Information* with the use of either STI format over a conventional LANTIRN implementation (Figure 32).

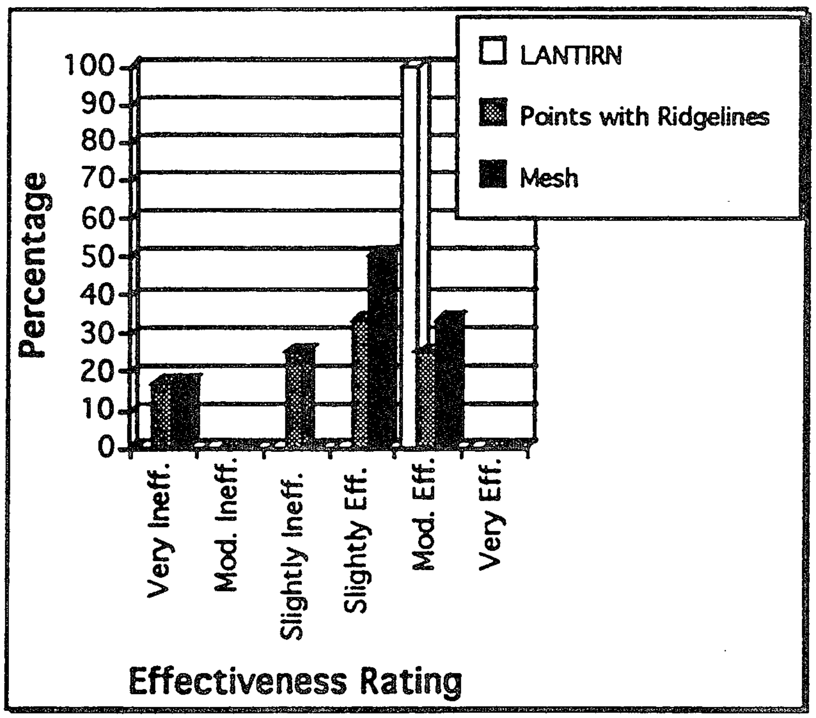


Figure 32
Overall Altitude Information Effectiveness

The next question addresses pilot *Confidence in using the LANTIRN/STI suite in Low Level flight.* The Unconfident ratings are from the same pilot (the difference in Bar height is an artifact of one fewer response for the Points with Ridgelines condition.) It can be seen that, on the whole, pilots indicate a positive improvement in confidence in Low Level flight with a combination of LANTIRN and STI (Figure 33).

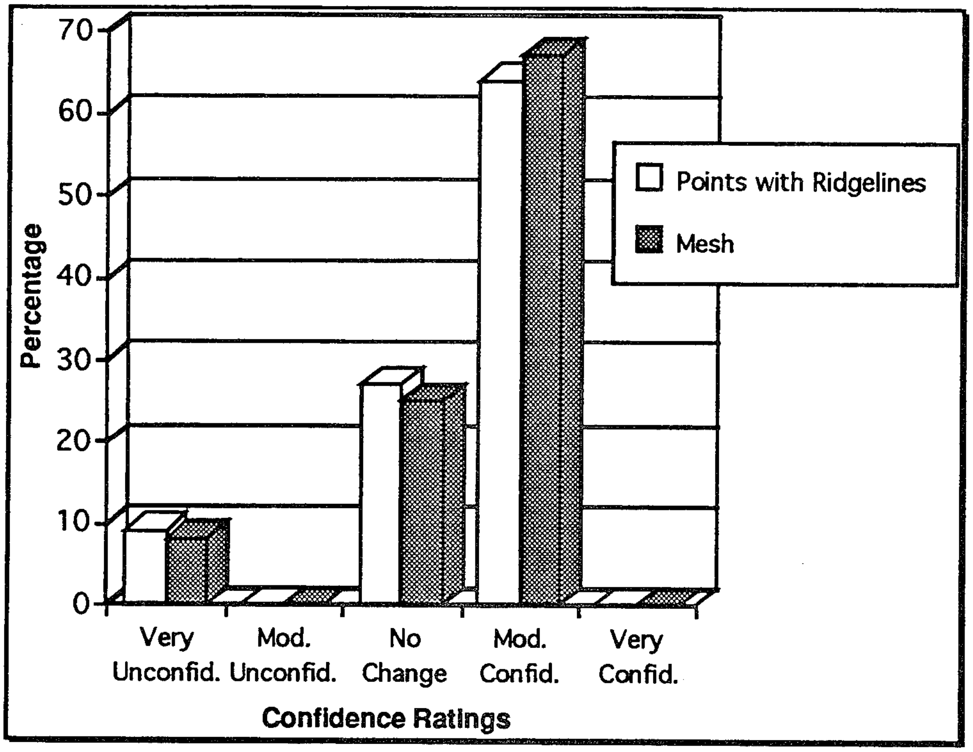


Figure 33
Confidence in Low Level Flight as a Result of LANTIRN/STI Combination

8.2.2.2 Terrain Masking. The pilot's abilty to use the surrounding terrain dramatically decreases an enemy's chance of detecting the aircraft, thereby increasing the pilot's chance of survival. The pilot's report a marked improvement with the use of STI in choosing alternative flight paths and utilizing terrain masking tactics.

The pilot's subjective ratings indicate that there was a gain in *Terrain Awareness for Choosing Alternative Flightpaths* with the use of either STI format over a conventional LANTIRN implementation (Figure 34). There seems to be an advantage for the Mesh format over the Points with Ridgelines format.

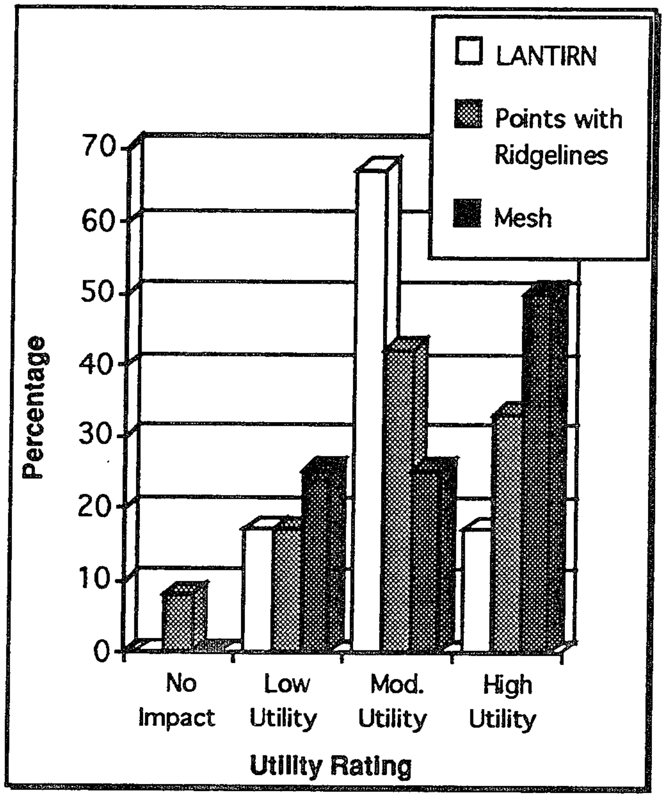


Figure 34
Terrain Awareness Utility for Choosing Alternate Flight Paths

The pilot's subjective ratings indicate that there was a marked gain in the ability to *Egress from a Target Area using Terrain Masking* tactics with the use of either STI format over a conventional LANTIRN implementation (Figure 35).

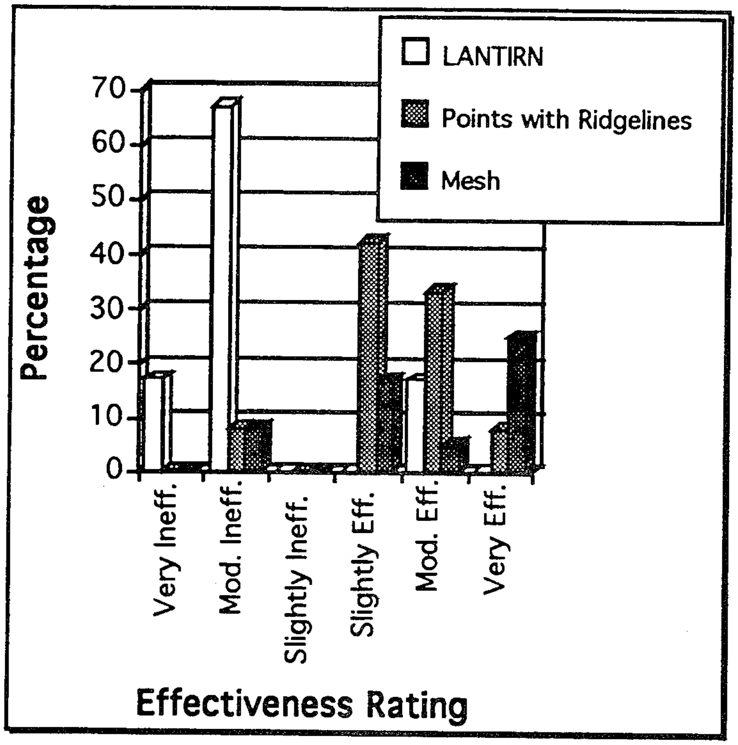


Figure 35
Target Area Egress Effectiveness using Terrain Masking

8.2.3 Survivability – Threat Reaction. Another facet of survivability is to defeat enemy surface-to-air missiles that are launched at the aircraft. There are two aspects to maneuvering to defeat a missile (see Section 7.4.2.1 Threat Reaction for a discussion of the missile launch model), aggressive maneuvering close to the ground and high G loads.

The aggressive maneuvering to defeat the missile must be close to the ground in order to avoid presenting the aircraft as a target to another missile battery. In order to maneuver close to the ground it is mandatory for the pilot to have awareness of the terrain around the aircraft in order to avoid inadvertently flying into it.

High G loads are required to break the lock of the missile's homing device.

The pilot's subjective ratings indicate that there was a gain made in *Altitude and Attitude Information Effectiveness* during a reaction to a threat (SAM launch) using STI relative to what is provided from LANTIRN. It appears that the Mesh format, with more favorable ratings, was favored over the Points with Ridgelines format (Figure 36).

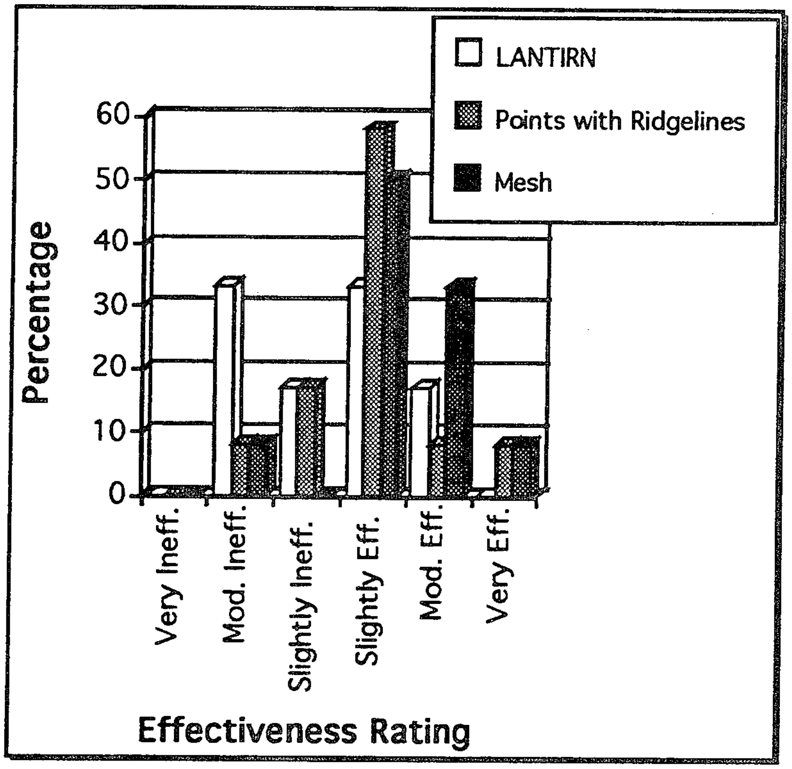


Figure 36
Altitude/Attitude Information Effectiveness during Threat Reaction

The pilot's subjective ratings indicate that there was a marked gain in keeping *Terrain Awareness with maneuvering at High G's during Threat Evasion* with the use of either STI format over a conventional LANTIRN implementation (Figure 37).

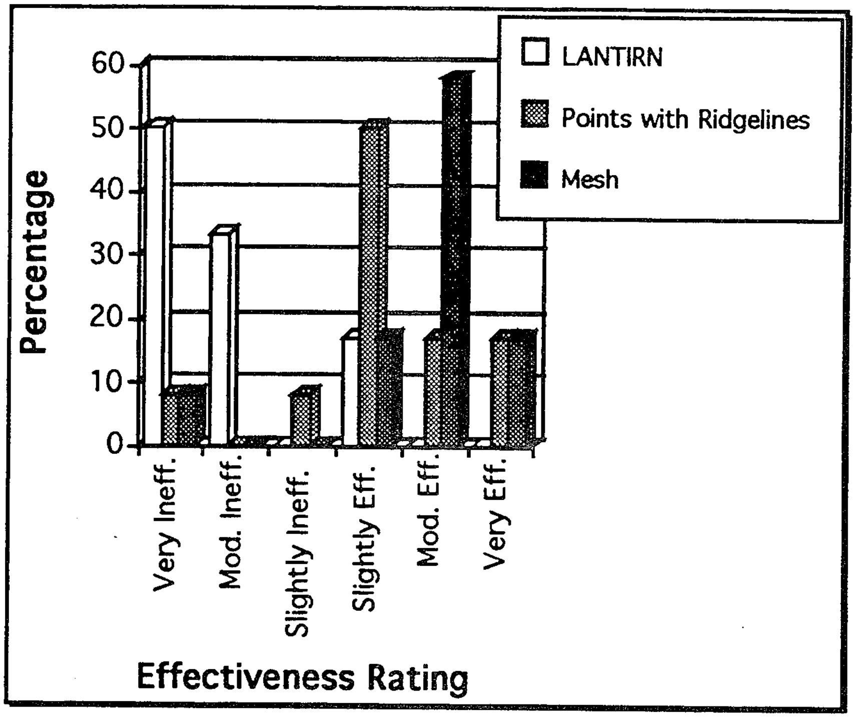


Figure 37
Terrain Awareness Effectiveness at High G's during Threat Evasion

8.2.4 Overall Effectiveness. The following section is intended to present the results of questions geared to assess the overall utility or effectiveness of the STI concept as well as determined which implementation was preferred overall (No STI, Points with Ridgelines, or Mesh).

The pilot's subjective ratings indicate that STI, used in conjunction with LANTIRN, was judged to be of benefit in terms of *Overall Effectiveness*. There appears to be an advantage for the Mesh format over the Points with Ridgelines format (Figure 38).

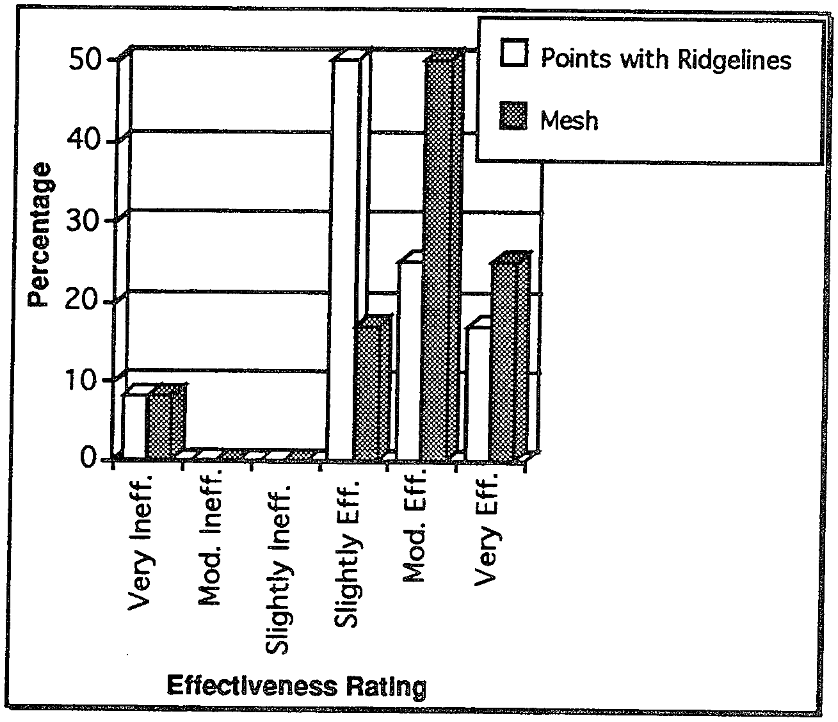


Figure 38
Overall Effectiveness

As was mentioned in an earlier section on weapon delivery, one of the most significant operational benefits to the STI implementation is the ability of the pilot to see the ground when viewing off-axis (outside the LANTIRN field-of-view) under conditions of low visibility. The pilots were asked to directly compare *LANTIRN only versus the combination of LANTIRN/STI for Comfort of Viewing Off-Axis* (Figure 39).

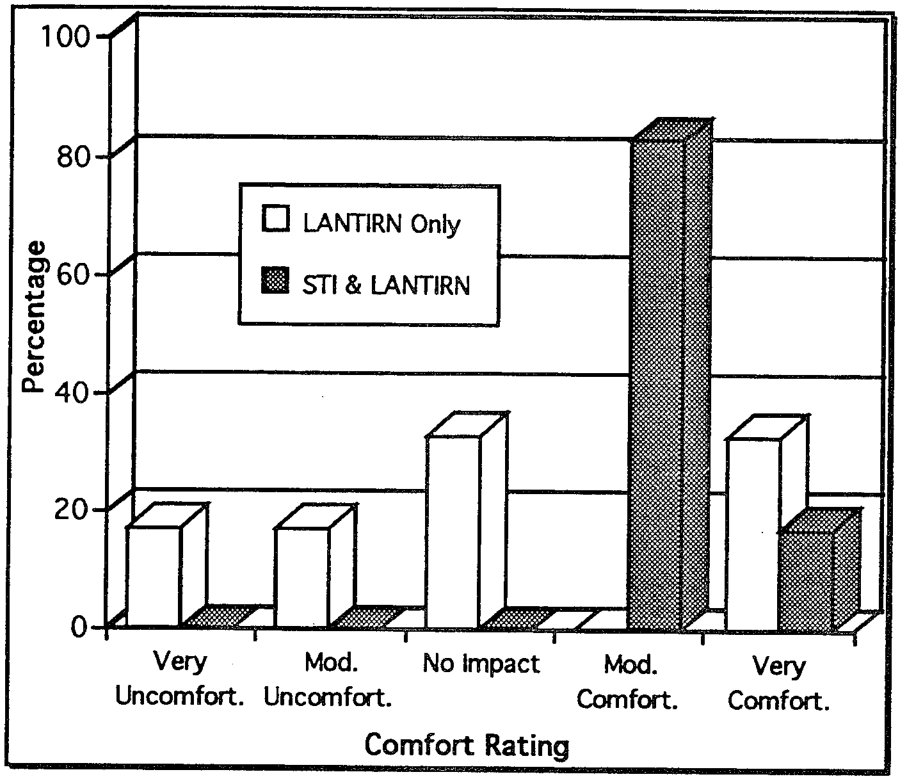


Figure 39
Ratings of Comfort for Off-Axis Viewing

The pilots were asked to provide an *Overall Rating of Operational Utility*. Both STI formats were preferred over a LANTIRN only implementation (Figure 40). There was a slight advantage for the Mesh format over the Points with Ridgelines format.

	Pilots						
	P1	P2	P3	P4	P5	P6	Avg. Rating
Mesh	3	1	1	1	1	1	**1.3**
Points w/Ridgelines	*	3	1	1	2	2	**1.8**
No STI	1	2	3	2	3	3	**2.3**

1 – High to 3 – Low

Figure 40
Overall Rating of Operational Utility

8.2.5 Comments. The following contains a summary of pilot comments/impressions obtained during debriefings and questionnaire responses.

LANTIRN

Positive Comments:
- Good altitude awareness below and straight ahead
- Works fine in good FLIR conditions

Other Comments:
- Lack of off-axis capability
- Limited TFR envelope
- Spatial disorientation is easy to induce
- Difficult to reattack
- Great majority of time fixed in the HUD
- Route selections must be preplanned from a map

SYNTHETIC TERRAIN IMAGERY

- Preferred Mesh over Points with Ridgelines

Positive Comments:
- Allowed target egress plan to be dynamic in accounting for terrain
- Much improved terrain awareness
- STI coupled with LANTIRN increased confidence level at low altitude
- Made reattack easier and more dynamic
- Allows for alternate flight paths based on terrain
- Greatly expands LANTIRN maneuvering limits

Other Comments:
- Doesn't provide much altitude awareness because of limited low altitude cues in synthetic terrain
- Depth perception is difficult
- Misregistration of STI against terrain is a serious problem.

Overall Impressions:
- Misregistration and inaccuracies of STI are the limiting factor.
- The system has great potential, but probably not as a standalone sensor
- Coupled with TFR and FLIR, STI has the potential to enhance terrain awareness
- The STI formats presented were not adequate to greatly improve terrain awareness, altitude awareness, and maneuverability.
- There is the potential to "close" the cockpit from the laser threat and to become more stealthy using STI
- STI has limited utility when the pilot can see the ground
- STI increases the time the pilot can fly in limited or zero visibility.
- Could allow for tactical maneuvering under IMC conditions
- HMD symbology should look like HUD symbology (Stroke)
- Synthetic imagery should look more like FLIR imagery (Raster)
- Terrain should extend to the horizon
- Should give a realistic terrain rendering instead of lines or points

8.3 Objective Results. There were a number of predictions about how STI could improve performance in terms of weapon delivery and survivability made in Section 7.7.1. In this section a comparison will be made between the predicted and actual performance to determine if there were any improvements.

Each measure was analyzed using a repeated-measures ANOVA. The results of the ANOVA are only included if in fact the test resulted in a significant effect.

Again, the reader should bear in mind that there was a misregistration between the world scene presented on the dome and the STI. The misregistration between the two scenes was more pronounced in the rugged terrain condition. A number of objective measures reported ANOVAs that found a significant interaction between STI format and terrain type (flat vs. rugged), this should be taken "with a grain of salt" due to the misregistration confound inherent in the simulation evaluation. This is not to say that STI only benefits the pilot in flat terrain, what is meant is that this study does nothing to clarify the utility of STI, from a performance improvement standpoint, in rugged terrain conditions.

8.3.1 Weapon Delivery. The first area of performance to be examined is weapon delivery. It was hypothesized that STI, which provides the pilot with an image of the surrounding terrain off boresight, would allow the pilot to fly lower and allow off-axis viewing thereby providing the capability to keep a target in view during maneuvering for reattack.

It was predicted that STI would allow the pilot to fly a *Lower Average Altitude Flown in the Target Area, both initial Attack and Reattack.* An interaction trend was found between STI Format and Route Type for *Average Altitude* $F(2,50)=2.57, p<.08$. As can be seen in the Figure below, the STI formats allow the pilot to fly lower in the flat terrain condition than the NO STI condition (Figure 41). Interestingly, the there is no discernable difference in format type for the rugged terrain condition. Average altitude in the rugged terrain condition is <u>greater</u> for the STI formats but lower for the No STI condition.

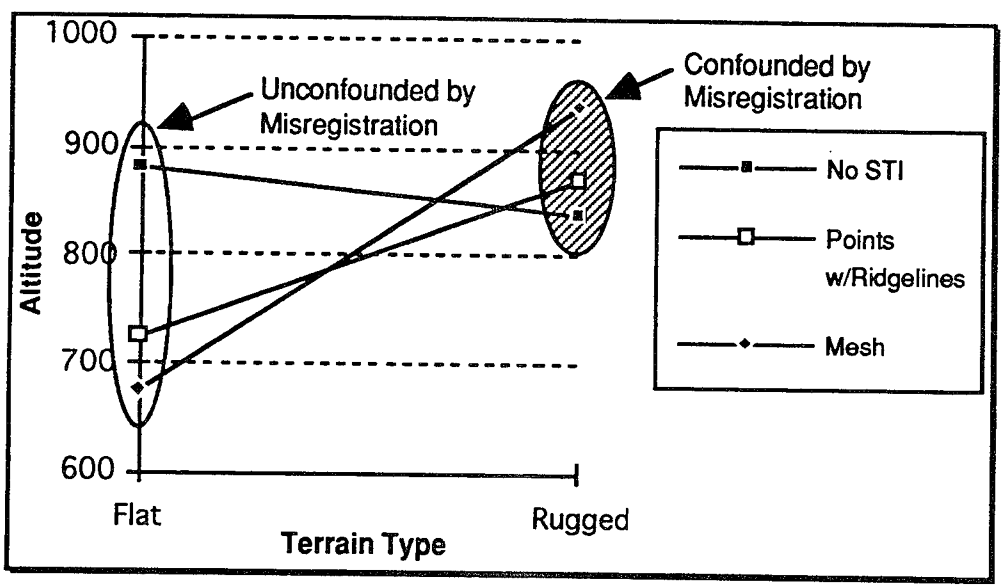


Figure 41
Weapon Release Segment - Average Altitude

An interaction trend was found between STI Format and Route Type for *Average Altitude in the Target Area*, $F(2,50)=3.69$, $p<.03$. As can be seen in the Figure below, the STI formats allow the pilot to fly lower in the flat terrain condition than the NO STI condition (Figure 42). As was seen for Average Altitude, the there is no discernable difference in format type for the rugged terrain condition. The STI formats had the lower altitudes over the target than the No STI condition.

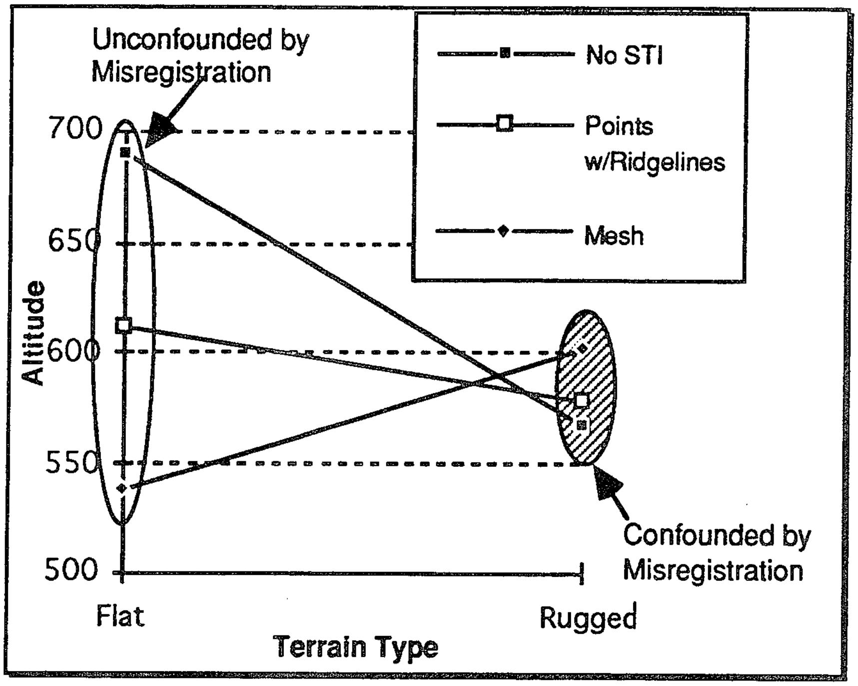


Figure 42
Weapon Release - Altitude in Target Area

The pilots were instructed to reattack as soon as possible, yet no significant difference was found for *Time in Reattack* (see Table 11) for the three different STI format conditions. It was predicted that STI would provide an advantage in terms of less time required for the reattack. This hypothesis was based upon the idea that pilots could keep the target area in sight during the reattack, which they could, but that did not guaranty that a visual fix on the target, within the target area, could be maintained during the reattack.

Table 11. Time in Reattack

No STI	Points w/ Ridgelines	Mesh
165 sec	177 sec	192 sec

No significant difference was found for the prediction of *Distance Flown Off Target Before Reattack* (see Table 12). It was predicted that STI would provide an advantage in terms of less distance flown away from the target before reattack, because it was thought that the pilot could keep the target area in view using the STI.

Table 12. Distance Flown Off Target Before Reattack

No STI	Points w/ Ridgelines	Mesh
13 nm	14.9 nm	12.9 nm

No significant difference was found for the prediction of *Time Spent Gazing Off-Axis for Target Acquisition* (see Table 13). It was predicted that STI would provide an advantage in terms of time spent viewing off-axis, although in the LGB delivery scenario there is no operational advantage to be gained by off-axis viewing (so this hypothesis only applies to the Mk-82 delivery mode). The lighting conditions for the test runs were dusk progressing to nighttime darkness, so the only utility to off-axis gazing was to avoid terrain in the direction of turns. Although not statistically significant, an advantage for the STI formats can be seen in the table below.

Table 13. Time Spent Gazing Off-Axis for Target Acquisition

No STI	Points w/ Ridgelines	Mesh
49.6 sec	66.2 sec	56.9 sec

No significant difference was found for the prediction of *Percentage of Successful Weapon Deliveries* (see Table 14), but there was a significant difference in the number of successful ordinance delivered based upon terrain type, which is misleading. Weapon delivery success was defined as deviation (3 milliradians) between the designation and the Continuously Computed Impact Point (CCIP), there is an inherent difference in weapon release accuracy requirements between the two ordinance type

Table 14. Percentage of Successful Weapon Deliveries

	Terrain Type	
STI Format	Flat	Rugged
No STI	12 of 12	2 of 20
Points	12 of 12	1 of 19
Mesh	12 of 12	2 of 20

8.3.2 Survivability – Pilotage. The next area of performance to be examined is basic pilotage and increasing the pilot's chance of survival. It was hypothesized that STI, which provides the pilot with an image of the surrounding terrain off boresight, would allow the pilot to fly lower, taking advantage of terrain masking tactics.

The first measure of increased survivability using STI was the number of inadvertenct ground contacts made during the course of the simulation. It was predicted that there would be *Fewer Controlled-Flight-Into-Terrain incidents with STI.* The total number of CFIT events was very low, considering the missions flown were low-level attack. There were 5 total CFIT events, see Table 15 below.

Table 15. Fewer Controlled-Flight-Into-Terrain incidents with STI

Mission Segment	STI Format	FLIR Quality	Terrain Type
Threat Reaction	Points	Poor	Rugged
En Route	Mesh	Poor	Rugged
En Route	No STI	Poor	Flat
En Route	Mesh	Good	Flat
En Route	Mesh	Good	Rugged
Weapon Delivery	Mesh	Poor	Rugged

No significant difference was found for the prediction of *Average Altitude* (see Table 16). It was predicted that STI would provide an advantage in terms of lower altitude flown. Although not statistically significant, it can be seen in the table that there is an advantage for the STI formats in terms of lower average altitude flown.

Table 16. Average Altitude

No STI	Points w/ Ridgelines	Mesh
982 ft	810 ft	850 ft

No significant difference was found for the prediction of *Variability in Altitude* (see Table 17). It was predicted that STI would provide an advantage in terms of less variability in altitude flown. Although not statistically significant, it can be seen in the table that there is an advantage for the STI formats in terms of less variability in altitude flown.

Table 17. Variability in Altitude

No STI	Points w/ Ridgelines	Mesh
406 ft	174 ft	280 ft

A significant interaction was found between STI Format and Route Type for *Average Terrain Height Overflown* $F(2,53)=4.07, p<.02$. As can be seen in the Figure 43, the STI formats provide the pilot with an advantage in seeking out terrain masking routes in the flat terrain condition, but in fact seem to do worse than with the No STI over rugged terrain.

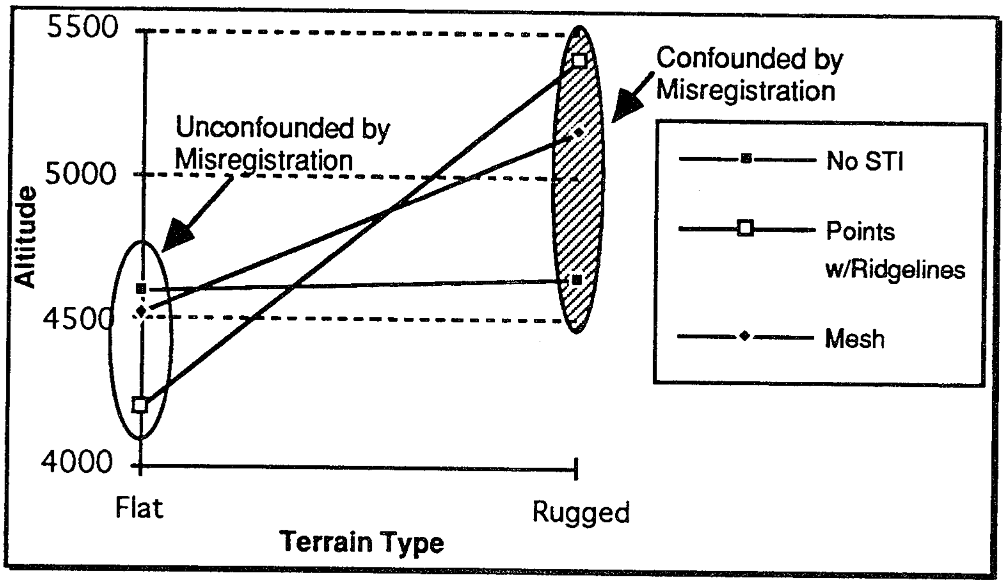


Figure 43
En Route Segment - Average Terrain Height Below Aircraft

A significant three-way interaction was found between STI Format, FLIR Image Quality, and Route Type for *Maximum Terrain Height Overflown* $F(2,53)=3.68$, $p<.03$. As was seen for the previous variable (Average Terrain Height Overflown), the STI formats provide the pilot with an advantage in seeking out terrain masking routes in the flat terrain condition, but in fact seem to do worse than with the No STI over rugged terrain, except for the No STI condition with a good FLIR image (Figure 44). In general the poor FLIR image results in higher terrain being overflown.

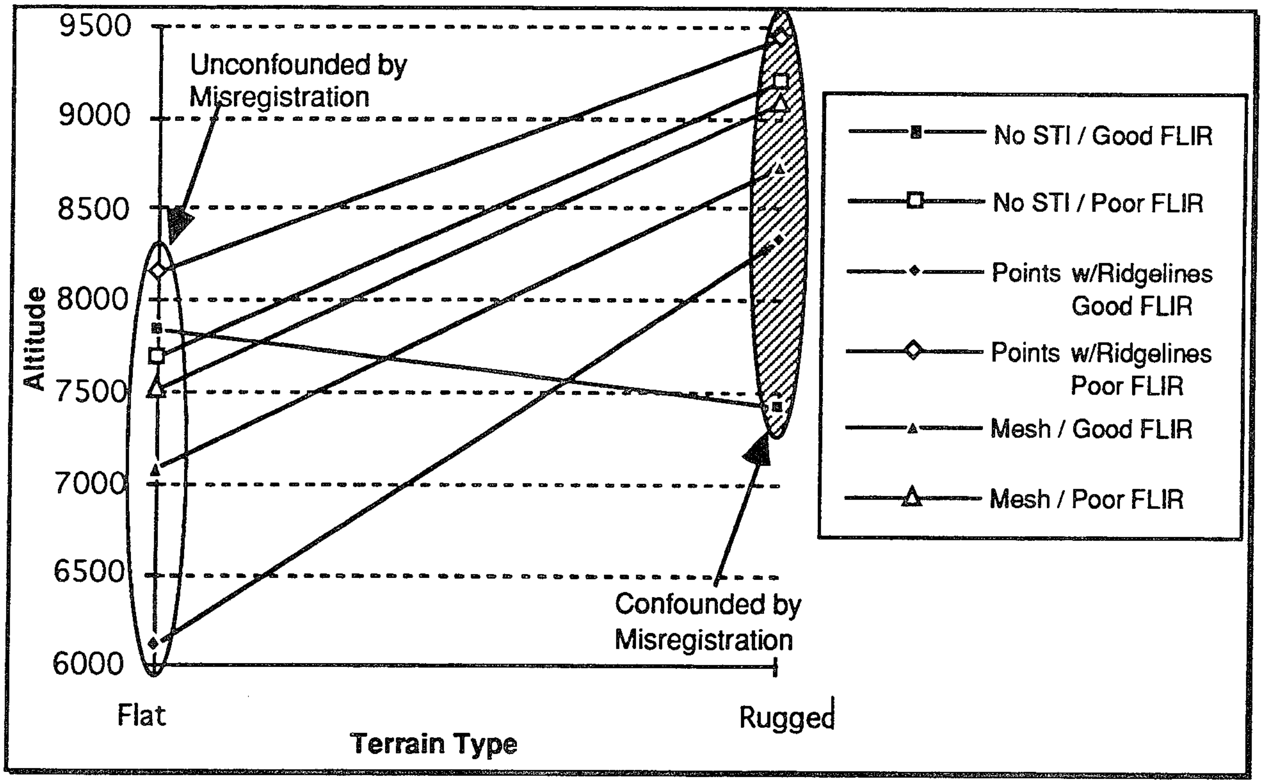


Figure 44
En Route Segment - Maximum Terrain Height Below Aircraft

A significant interaction was found between STI Format and Route Type for *Average Deviation between Average Altitude and MEA (terrain masking tactics)* $F(2,53)=5.71$, $p<.006$. To take advantage of terrain masking tactics, the pilot must fly low winding through the surrounding terrain (Figure 45). This type of flight should result in a higher deviation between safe Minimum En route Altitude (MEA) and actual altitude flown. Surprisingly, in the rugged terrain condition, the LANTIRN only (No STI) condition provided the highest deviation.

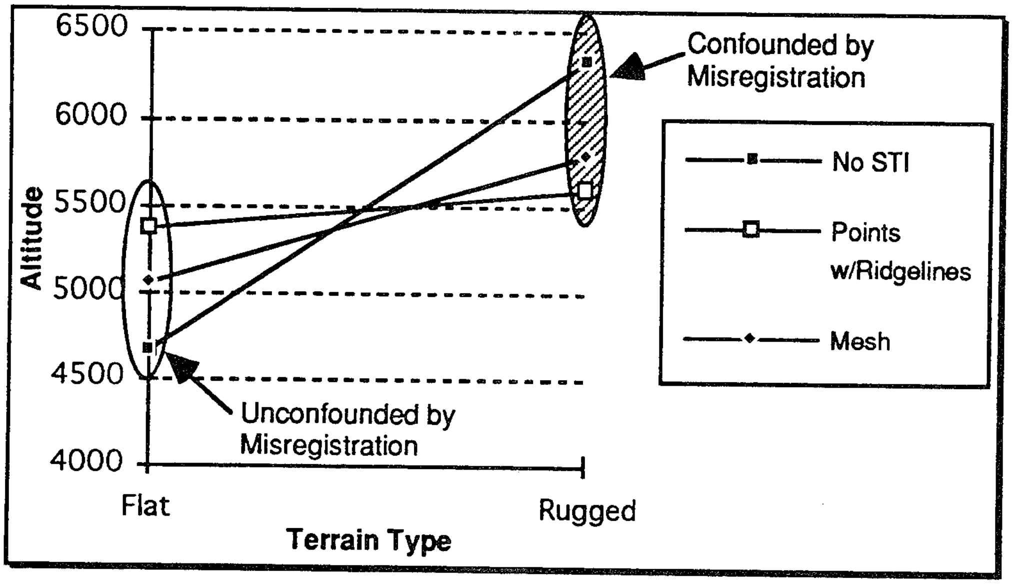


Figure 45
En Route Segment - Average Deviation between MSL Altitude and MEA

Pilots were instructed to fly as fast as possible, as long as they were comfortable. No significant difference was found for the prediction of *Greater Average Velocity* (see Table 18). Although not statistically significant, it can be seen in the table that there is an advantage in terms of faster average velocity for the STI formats.

Table 18. Greater Average Velocity

No STI	Points w/ Ridgelines	Mesh
519 kts	540 kts	535 kts

No significant difference was found for the prediction of *Percentage of Time Flown in IFR Weather Conditions* (see Table 19). Although not statistically significant, it can be seen in the table that there is an advantage for the STI formats in terms of time spent in IFR weather.

Table 19. Percentage of Time Flown in IFR Weather Conditions

No STI	Points w/ Ridgelines	Mesh
40%	48%	46%

8.3.3 Survivability – Threat Reaction. Another aspect to survivability is the ability to avoid detection by the enemy and successful maneuvering to defeat enemy missiles once launched.

No significant difference was found for the prediction of *Average Altitude in Area with SAM Threat* (see Table 20).

Table 20. Average Altitude in Area with SAM Threat

No STI	Points w/ Ridgelines	Mesh
1669 ft	1649 ft	1709 ft

No significant difference was found for the prediction of *Average G Loading in Response to Missile Launch* (see Table 21).

Table 21. Average G Loading in Response to Missile Launch

No STI	Points w/ Ridgelines	Mesh
2.9 G's	3.4 G's	3.0 G's

No significant difference was found for the prediction of *Number of Missiles Launched* or *Number of Missile Defeated.* Although it can be seen that the Mesh condition was the most successful format in terms of minimizing launches (see Table 22).

Table 22. Number of Missiles Launched or Number of Missile Defeated

No STI	Points w/ Ridgelines	Mesh
88% of 17 launched	76% of 17 launched	85% of 13 launched

8.3.4 Survivability – Weapon Delivery. Finally, a key to survivability is timely egress from the target area.

Although pilots were instructed to establish egress heading "as soon as possible" there was no significant difference found for the prediction of *Time Required for Target Area Egress* . (The egress heading clock was stopped when pilots brought the aircraft within 2° of the egress heading.) Although it can be seen that the Mesh had the lowest average time required for target area egress (see Table 23).

Table 23. Time Required for Target Area Egress

No STI	Points w/ Ridgelines	Mesh
49.5 sec	54.3 sec	35.3 sec

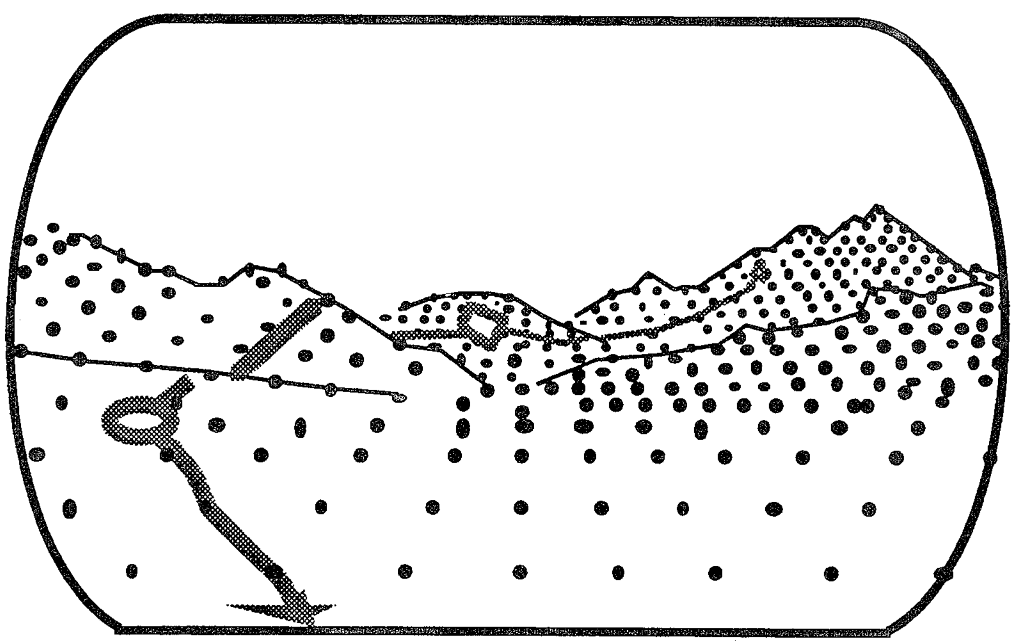
9. Conclusion

Although hampered by the misregistration problem, as well as compromises in test planning and procedures due to limited resources, this program demonstrated that Synthetic Terrain Imagery in a Helmet-Mounted Display provided pilots of tactical aircraft with advantages over current technology in terms of weapon delivery and survivability.

9.1 Correction of Misregistration. One major limitation of the full mission simulation portion of this study was a misalignment of the synthetic terrain image to the outside visual scene. The misalignment arose because of the simulator visual scene was rendered using a round earth model while STI was rendered using a flat earth coordinate system. This problem has been solved so that the STI capability can be carried forward into the Mission Reconfigurable Cockpit (MRC) program.

9.2 Future Directions. The concept of synthetic terrain appears to be a usable approach for providing the pilot off-axis terrain features. Most pilots agreed that presenting synthetic terrain in an HMD was a very useful concept for allowing off-axis viewing of the surrounding terrain, greatly improving situational awareness. Overall, synthetic terrain imagery has the potential to improve night mission performance under poor weather conditions.

The most intuitive addition to current STI formats would be to superimpose mission related coordinates (waypoints, initialization points, target designation) over the ground. This would enable the pilot to utilize off-axis viewing for terrain masking tactics or reattack of a target without reference to any symbology in the HUD, such as the flight path marker. This concept is shown in Figure 46.



BC-HMD-02

Figure 46
STI with Flight Path Superimposed over Terrain